Original Paper

Enhancing cognitive performance and emotional well-being via Nature-induced learning environments.

Insights from neuro-architecture research

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Keywords: neuro-architecture; neuropsychology; built environment; environmental psychology; cognitive architecture; learning environments.

List of Abbreviations: ADHD: Attention-Deficit / Hyperactivity Disorder; ANOVA: Analysis of Variance; ART: Attention Restoration Theory; BDST: Backward Digit Span Test; BVRT: Benton Visual Retention Test; DSM-V: Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition; DSST: Digit Symbol Substitution Test; DST: Digit Span Test; EEG: Electroencephalogram; FAA: Frontal Alpha Asymmetry; NASA-TLX: NASA Task Load Index; PRS: Perceived Restorativeness Scale; PRT: Prospect Refuge Theory; SRT: Stress Reduction Theory; ST: Stroop Test.

Abstract. *This study, involving 22 participants, explored the impact of nature-induced design on cognitive performance and emotional well-being in educational settings. Key metrics included EEG-based Frontal Alpha Asymmetry (FAA), Normalized Alpha brainwave activity, the Perceived Restorativeness Scale (PRS), and the NASA Task Load Index (NASA-TLX). In 'more biophilic' learning environment, i.e., Studio, PRS scores significantly increased, indicating higher perceived restorativeness, while NASA-TLX scores (56.65 in the Studio versus 50.65 in the Seminar Hall, i.e., 'lesser biophilic' learning environment) indicated greater cognitive engagement in the Studio. Notably, the Studio exhibited higher left-aligned FAA outcomes, revealing a significant relationship between FAA and the built environment ($\chi^2 = 12.239$, $p < 0.001$). The study identified substantial effects, with a significant variance for PRS-11 ($F = 12.134$, $p = 0.001$) and moderate influence for NASA-TLX ($F = 4.374$, $p = 0.043$). ANOVA analysis revealed significant differences in cognitive performance across various tests: BVRT ($F = 9.195$, $p = .004$), DST ($F = 20.230$, $p < .001$), BDST ($F = 19.563$, $p < .001$), ST ($F = 4.319$, $p = .044$), DSST ($F = 15.400$, $p < .001$), and the overall Cognitive Score ($F = 27.508$, $p < .001$), indicating a robust effect of the built environment on cognitive functions. This research demonstrates that nature-infused educational environments significantly enhance critical cognitive processes essential for learning, suggesting their potential in environmental design for cognitive and emotional development. However, it* *acknowledges limitations, such as sample variation and experimental settings, and encourages further investigation in diverse contexts and long-term effects.*

1. Introduction

In contemporary society, where individuals spend the majority of their time within or around built environments, the symbiotic relationship between architectural design and human psychology emerges as a focal point of scholarly investigation. The repercussions of architectural composition on involuntary attention, behavioural patterns, and cognitive functions have garnered significant attention, underscoring the imperative to align built environments with the intricacies of human psychological well-being (Kassarning et al., 2018). Within educational contexts globally, students grapple with pervasive academic stress and anxiety, phenomena intricately interwoven with mental health concerns. A burgeoning body of research posits that prolonged exposure to suboptimal educational environments may catalyse the development of psychological challenges, affecting mood and potentially leading to severe mental disorders (Margraf et al., 2020). The multifaceted impact of built environments on mental health spans direct considerations such as illumination levels, background noise, indoor conditions, and pollution, as well as indirect factors including classroom congestion, furniture design, and aesthetic elements (Asim et al., 2021). Critical considerations in the design of learning spaces extend to the cognitive implications of inadequate illumination and ambient noise, the discomfort induced by suboptimal temperature control and ventilation, and the potential hindrance to cognitive performance resulting from distractions and elevated stress levels in crowded educational settings (Castilla et al., 2023). Ergonomic challenges posed by uncomfortable furniture further impede students' concentration and participation. Monotony in design elements may contribute to reduced engagement and cognitive function, while limited access to outdoor spaces may deprive students of the benefits associated with biophilic design, impacting both cognitive and mental well-being (Ko et al., 2020). Challenges stemming from inefficient floor plans, unclear navigation aids, and complex layouts within learning environments present additional stressors that can contribute to tension and anxiety, ultimately impairing cognitive abilities (Maxim et al., 2023). Environmental factors such as unpleasant smells, visual distractions, and clutter introduce further complexities, disrupting students' focus and concentration in academic pursuits. Moreover, the absence of personalization options within learning spaces and non-accessible buildings pose potential obstacles for students with disabilities, impacting engagement and social and cognitive growth (Klatte et al., 2010). This intricate interplay between architectural design, environmental variables, and cognitive well-being underscores the urgency and significance of investigating the impact of learning-built environments on students' cognitive functions within the scope of this research endeavour (Aries et al., 2015).

1.1. Cognition: attention, memory, perception and executive function

Cognitive functions, encompassing attention, memory, perception, and executive function, form the bedrock of essential mental processes, facilitating the reception, interpretation, and response to environmental stimuli. These cognitive processes are integral to the execution of daily tasks, problem-solving, decision-making, and overall cognitive performance (Demetriou et al., 2020; Weinstein et al., 1977). Attention, a foundational cognitive ability, involves the focused concentration on specific stimuli while concurrently disregarding others. It manifests in various forms, including alternate, divided, sustained, or selective attention, contingent upon situational demands and task requirements (Marchand et al., 2014; Bodenhausen & Hugenberg, 2011). Memory, another pivotal cognitive process, encompasses the encoding, storage, and retrieval of information for subsequent utilization. This multifaceted process involves the conversion of sensory information into a storable format, the retention of encoded information over time, and the retrieval of stored data as needed. Memory is further categorized into long-term memory, working memory, and sensory memory (Ashcraft, 1989; Dolcos et al., 2020). Perception, an intricate cognitive function, pertains to the construction of meaningful interpretations from sensory data acquired from the environment. This process involves the integration of diverse sensory inputs, such as visual, auditory, tactile, and olfactory cues, to form a coherent representation of the surroundings, enabling recognition of objects and events (Bruner & Postman, 1949; Bodenhausen & Hugenberg, 2011; Cahen & Tacca, 2013). Executive function, comprising sophisticated cognitive processes, serves to manage and coordinate other cognitive skills. It encompasses planning, organizing, initiating and ceasing actions, monitoring performance, and adapting to changing circumstances (Miller & Wallis, 2009; Roebers, 2017). Essential components of executive function include controlling impulsive behaviour, exercising cognitive flexibility through task-switching, and proficiently strategizing and organizing tasks for goal-directed behaviour, problem-solving, self-control, and decision-making (Gilbert & Burgess, 2008; Benedek et al., 2014).

The synergistic operation of these cognitive processes significantly influences how individuals perceive and interact with their environment. To optimize learning, daily functioning, and overall cognitive performance, these cognitive domains necessitate peak functionality (Choi et al., 2014; Ward et al., 2016). Factors such as age, health, environment, and training can modulate the efficacy of specific cognitive processes, highlighting the multifaceted nature of cognitive function within the context of this investigation (Cassrino & Setti, 2015).

1.2. ART, SRT, PRT and Arousal Theory

The psychologists Rachel and Stephen Kaplan developed the Attention Restoration Theory (ART) in the 1980s. According to the hypothesis, exposure to Restorative Environments (often natural settings) helps replenish one's mental capacities and cognitive abilities, especially directed attention, which can become depleted or worn out after repeated use (Kaplan & Kaplan, 1989). To combine elements of nature and encourage mental repair, ART has been applied to a variety of fields, including urban planning, architecture, healthcare, education, and workplace design (Ohly et al., 2016; Neilson et al., 2019). Exposure to restorative environments has been linked to a better mood, less stress, better cognitive function, more creativity, and general wellbeing (Pasanen et al., 2018; Felsten, 2009; Asim et al., 2023; Moreno et al., 2018; Asim & Shree, 2019). The ART states that it is crucial to incorporate natural components into environments and design spaces that promote effortless attention to replenish mental resources, which will lead to better cognitive performance and psychological health in general (Kaplan & Kaplan, 1989; Kaplan et al., 1993).

According to ART, exposure to places with particular restorative features i.e., Restorative Environments, such as natural environments, can aid in the recovery of mental resources like attention. It emphasises how relaxing being in nature is and how easily it attracts attention (Joye & Dewitte, 2018). Improved cognitive function and lessened mental weariness are benefits of the restoration of attention. As stated by Ulrich (1991) and others, who support the Stress Reduction Theory (SRT), being exposed to natural settings can lower stress levels and accelerate the recovery process after stress. It emphasises how nature can have a good impact on emotions and bodily reactions, which can reduce stress and increase wellbeing (Ulrich et al., 1983; Luo & Jiang, 2022). The Prospect Refuge Theory (PRT), put forth by Appleton, focuses on how humans have evolved to choose locations that provide both prospects—views of their immediate surroundings—and refuges—areas of protection and camouflage. According to this theory, being in an environment with beautiful views and a sense of security or sanctuary can evoke pleasant emotional reactions, support attention restoration, and lower stress levels (Appleton et al.,1975; Dosen & Ostwald, 2016; Gatersleben & Andrews, 2013).

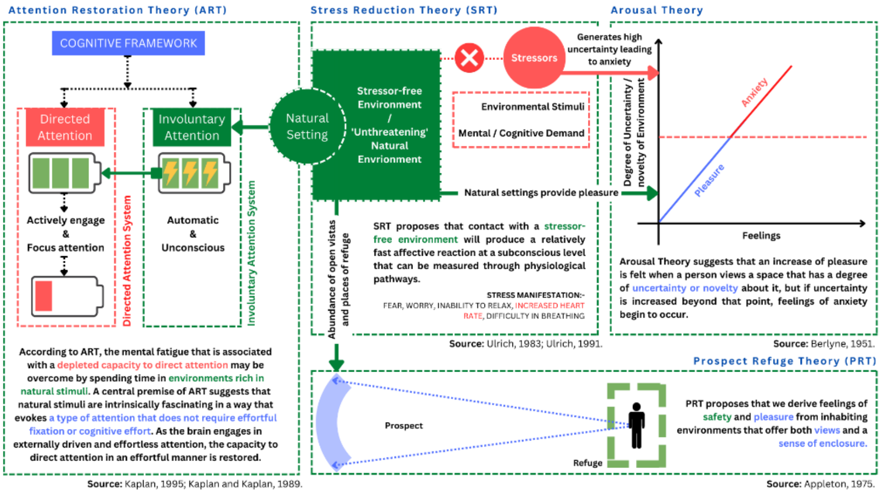

Figure 1. Theoretical frameworks of recovery from stress, and emotional satisfaction with respect to the built environment: attention restoration, stress reduction, arousal, and prospect & refuge (Source: Asim et al., 2023). HR is in https://ojs.unito.it/index.php/visions/article/view/9265/8309

According to the psychology-based Arousal theory, people look for the right amount of motivation or arousal in their surroundings. Both insufficient or excessive stimulation might cause discomfort or stress (Berlyne, 1963; Russell et al., 1980). Natural settings frequently offer the right amount of stimulation, bringing about a state of calm and lowering tension, which is consistent with the ART and SRT principles for decreasing stress. Asim et al. (2023) conducted a comprehensive analysis of various theoretical frameworks (shown in Fig.1), underscoring a common theme across each: the significant benefits of natural environments for enhancing human well-being, alleviating stress, and aiding in attention recovery. Their research highlights the multifaceted impact of natural elements, reinforcing the notion that, despite the distinct focus of each theory, they collectively affirm the importance of integrating natural materials and restorative factors into our surroundings to improve mental health and overall quality of life.

1.3. PRS and NASA TLX

Within the realm of environmental psychology, the Perceived Restorativeness Scale (PRS) is frequently employed as a measurement instrument, assessing an environment's potential for promoting psychological restoration. This scale is intricately linked with the Attention Restoration Theory (ART), positing that specific environmental settings have the capacity to alleviate mental fatigue and contribute to the replenishment of cognitive resources, particularly attention (Pasini et al., 2014; Korpela & Hartig, 1996). The PRS encompasses factors associated with environmental attributes conducive to restorative experiences, including fascination, being away, coherence, and compatibility with individual preferences. Respondents evaluate these characteristics based on their perceptions and interactions with the environment (Rai et al., 2019). PRS has become an important tool in environmental behaviour studies in recent years with urban design and architecture being one of the PRS's main fields of application. The scale is being used by researchers on a wider scale to assess the restorative potential of urban green areas, such as parks and gardens (Stragà et al., 2023; Hooyberg et al., 2022; Rai et al., 2020). This assessment is essential for creating cities that not only have a beautiful appearance but also exhibited residents' mental health and stress relief. Studies on workplace environments have another important use for the PRS. Here, the scale assists in analysing how various workplace layouts and the inclusion of natural features, in particular, might enhance worker productivity and well-being (Pasini et al., 2021; Craig et al., 2022). Research in educational establishments use PRS as a measure to evaluate how their surroundings affect the mental health of their students. Through the assessment of aspects like natural light, vegetation, and layout in educational institutions, the PRS facilitates comprehension of how these features improve cognition and lower stress levels in students (Asim & Shree, 2019; Stragà et al., 2023). When taken as a whole, these various uses of the PRS reflect how crucial it is to design spaces that are both functional and psychologically restorative.

Concurrently, the NASA Task Load Index (NASA-TLX), a multidimensional tool originally devised for assessing the workload of NASA pilots, serves as a comprehensive measure of the mental and emotional demands inherent in a given task (Hart & Staveland, 1988; Hart, 2006; Alaimo et al., 2020). This tool, adapted for application across various disciplines, involves users assigning numerical scores to each dimension while concurrently rating the perceived burden on individual subscales. The derivation of an overall workload score involves the weighted summation of these individual scores (Noyes et al., 2007).

1.4. EEG and its application in learning-built environment

Utilizing the non-invasive technique of electroencephalography (EEG), this study examines the electrical activity within the brain, providing valuable insights into various cognitive processes. EEG allows researchers to observe brainwave oscillations and event-related potentials, which serve as indicators of cognitive functions such as memory acquisition and retrieval, attentional allocation, and other related processes (Gotlib, 1998; Klimesch, 1999; Ball et al., 2009). Notably, the high temporal resolution of EEG renders it ideal for the real-time recording of cognitive changes. Across diverse learning-built environments, EEG serves as a proficient tool for monitoring student participation and attention during learning activities. This capability empowers educators and architects to optimize spatial layouts and configurations, strategically aligning with periods of heightened or diminished attention (Ramírez-Moreno, 2021; Azazzy et al., 2021; Cruz-Garza et al., 2022). Furthermore, EEG recordings have the capacity to capture emotional reactions and affective states, unveiling pivotal details regarding the influence of the built environment on students' emotional experiences. Incorporating positive design elements have further shown to enhance learning processes and contribute to improved memory retention (Arsalidou et al., 2016; Li et al., 2020; Hu et al., 2021). Moreover, EEG facilitates the identification of cognitively challenging or confusing spaces within a specific environment, thereby enabling potential design enhancements for enhanced navigation and spatial comprehension (Lin et al., 2021; Bower et al., 2022; Mavros et al., 2022).

In the study of brainwave oscillations, certain frequency bands have been linked to specific neuronal functions and states of consciousness. Delta waves, which have a frequency range of 1-4 Hz, are often connected with profound relaxation and the unconscious mind and are frequently seen during dreamless sleep. Theta waves, which occur between 4 and 8 Hz, represent a state that is close to consciousness, similar to that experienced during light sleep or intense meditation. Alpha waves, which range from 8 to 13 Hz, indicate a calm yet aware state, and are frequently present throughout restful wakefulness, and serve as a link between sensory and cognitive processes (Bhatti et al., 2016; Horlings et al., 2008). Beta waves, which range from 13 to 32 Hz, are indicative of an active, engaged mind and usually increase during periods of heightened attention or stress. Finally, gamma waves, which have frequencies more than 32 Hz, are indicators of high-level cognitive functioning and complicated information processing, since they represent intricate brain activity. These bands provide a spectral framework for comprehending the brain's changing physiological states as it interacts with and responds to its surroundings (Dziembowska et al., 2016). By measuring tension and relaxation responses to various environmental stimuli, EEG offers valuable insights for designing tranquil and stress-relieving zones within educational settings (Chen et al., 2020; Asim et al., 2023). This knowledge, in turn, informs the creation of environments that positively influence stress levels, ultimately contributing to enhanced learning outcomes (Hou et al., 2015).

Another important metric arising from within EEG studies is Frontal Alpha Asymmetry (FAA). It conveys information regarding the differences in alpha wave activity between the brain's left and right frontal regions. As mentioned earlier, alpha waves are a type of brain waves found in EEG recordings that are often connected to a relaxed wakefulness state (Smith et al., 2017; Mennella et al., 2017). Alpha power, or the frequency and intensity of alpha waves, in the brain's frontal lobes, is compared to determine FAA. According to the notion, psychological processes and emotions may be related to fluctuations in alpha power between the left and right sides of the frontal cortex (Javorska et al., 2012; Gollan et al., 2014). Studies have shown a potential link between FAA and an individual's ability to regulate and direct their attention. Greater asymmetry favouring the left frontal region, for instance, may be linked to improved attention and the capacity to restrict out unimportant distractions. The relationship between FAA patterns and sustained attention throughout extended activities is also of interest since it may have an impact on performance in professional or educational environments (Pérez-Edgar et al., 2013; Bagherzadeh et al., 2020). It has also been reflected in the studies that approach or avoidance motivation, which can impact decision-making processes, is associated with the FAA. Approach behaviours are frequently linked to left-frontal activity dominance, which may result in more proactive decision-making approaches (Kaur et al., 2020; Deng et al., 2023).

2. Material and Methods

2.1. Methods

The primary objective of this research article was to discern and analyse the different cognitive behaviours exhibited by students within two distinct learning-built environments—namely, a biophilic setting represented by 'the architecture studio' and a less biophilic counterpart represented by 'the seminar hall'. By undertaking a distinct investigation of cognitive functioning, restorativeness and perceived mental workload in these environments, the study aspires to provide empirical insights into the differential impact of presence of biophilic elements on the cognitive processes of students within educational settings.

2.2. Hypothesis

Grounded in the theoretical frameworks of Attention Restoration Theory (ART), Stress Reduction Theory (SRT), Perceived Restorativeness Theory (PRT), and Arousal Theory, the study posits that the learning-built environment exerts a significant influence on students' cognitive functions, including attention, memory, perception, and executive function. The investigation formulates four hypotheses to systematically examine these cognitive and restorative dimensions, as outlined in Table 1 and illustrated in Figure 2.

Hypotheses	Explanation
H1a	*The presence of the biophilic built environment will generate a positive approach i.e., Left aligned FAA.*
H1b	*The presence of the biophilic built environment will generate a higher Normalized Alpha i.e., induce feeling of calm or restoration or relaxation.*
H2a	*The presence of the biophilic built environment will generate a higher Perception of Restorativeness.*
H3a	*The presence of the biophilic built environment will generate a lower perceived workload score.*
H4a	*The presence of the biophilic built environment will generate a higher Cognitive Score.*

Table 1. Hypothesis being tested in the study with their explanation

These hypotheses collectively serve as a structured framework for the empirical investigation, guiding the analysis and interpretation of data collected within the study. The variables outlined in each hypothesis are strategically selected to capture distinct facets of the cognitive experience within different environmental conditions, providing a comprehensive understanding of the impact of biophilic elements on students' cognitive functions. The subsequent sections detail the methodology employed to test and validate these hypotheses rigorously.

2.3. Location and participants

The study was conducted at an institute of National importance, located between 870 and 900 meters above sea level in the Shivalik hills of the Himalayas, within the Himachal Pradesh region of India. This study aimed to discern the impact of learning environments characterized by variation in presence of biophilia on the cognitive functions, specifically attention, memory, perception, and executive function, among students, with a focus on their cognitive performance. A cohort of 22 participants, maintaining an equitable gender distribution i.e., 1:1 for Male: Female (calculation shown in Table 2) (Faul et al., 2007), enrolled in both bachelor's and master's programs, participated in the study, adhering to an age bracket of 18 to 26 years. The decision on the sample size was informed by a power analysis, underscoring the study's commitment to statistical reliability and validity. Adherence to Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-V) criteria guided the inclusion of individuals, who were screened for adult Attention-Deficit/Hyperactivity Disorder (Adult-ADHD), depression, and anxiety. Screening instruments such as the CES-D (Center for Epidemiologic Studies Depression Scale), GAD-7 (Generalized Anxiety Disorder 7), and ASRS-5 (Adult ADHD Self-Report Scale) were employed for this purpose (Ustun et al., 2017; Lolk, 2013). The utilization of these assessments aimed to pre-emptively identify and mitigate potential confounding influences arising from mental health issues, ensuring the participants' cognitive stability. Participants were additionally required to disclose any history of addictive behaviours, mental disorders, neurological conditions, or a combination thereof. This comprehensive screening process was integral to ensuring the study's integrity and the accurate interpretation of cognitive data by minimizing the influence of external factors on participants' cognitive functioning.

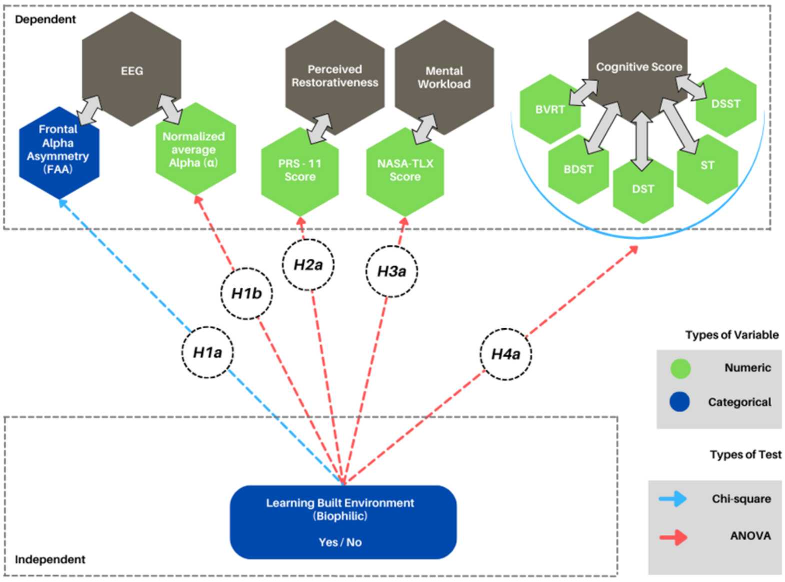

Figure 2. Demonstration of variable associations being tested with ideal statistical tests *(Source: Author).*

Test Family	Statistical Test	Effect Size	α	power (1-β)	Computed Sample Size
f-test	ANOVA: One way	0.8	0.05	0.95	22
chi square	Goodness of fit tests - Contingency Tables	0.8	0.05	0.95	21
	Adopted Sample Size				**22**

Table 2. Participant sample size calculation using G Power 3.1.

2.4. Learning environments

For this investigation, two distinct learning-centric environments were chosen within the campus setting, specifically denoted as a) Studio and b) Seminar Hall. The layout plan of both the learning environments is shown in Figure 3 and interior views in Fig. 4. The learning environment Studio is a significantly more biophilic in terms of its inherent access to nature from a ribbon window at lintel level on one side and a rear window running from sill to lintel level which offers views of dense pine forest and snow-clad mountains (as shown in Fig. 4-d). Whereas the learning environment Seminar Hall is significantly less biophilic in terms of its access to nature from only a rear window running from sill level to lintel level which offers outdoor views of a small, enclosed garden.

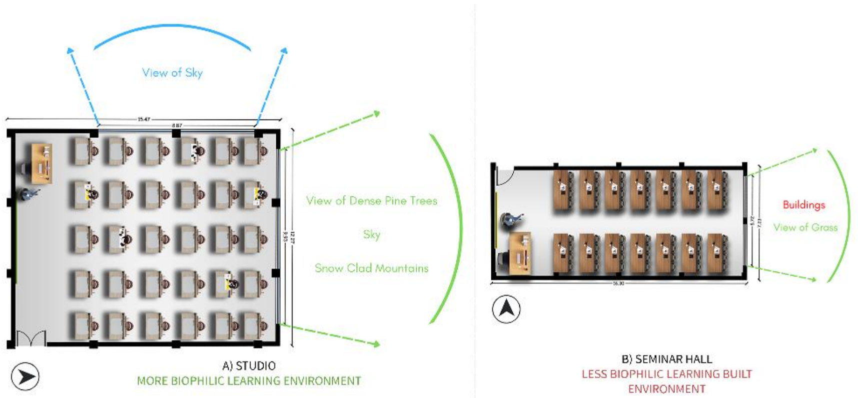

Figure 3. Layout plan of a) Studio: a more biophilic learning environment (left) and b) Seminar Hall: a less biophilic learning environment (right) (Source: Author).

Unlike majority of previous studies where the biophilic element (window or green wall in most cases) is kept in clear sight of the participant, this study adopts an indirect approach and brings the biophilic element as a passive visual element. These elements were positioned outside the direct focus zone of participants, who were aware of their presence without engaging in continuous visual contact. This setup aimed to explore the restorative effects of biophilic features on participants' cognitive states, even in the absence of direct interaction, positing that the mere awareness of these elements could positively influence the learning experience.

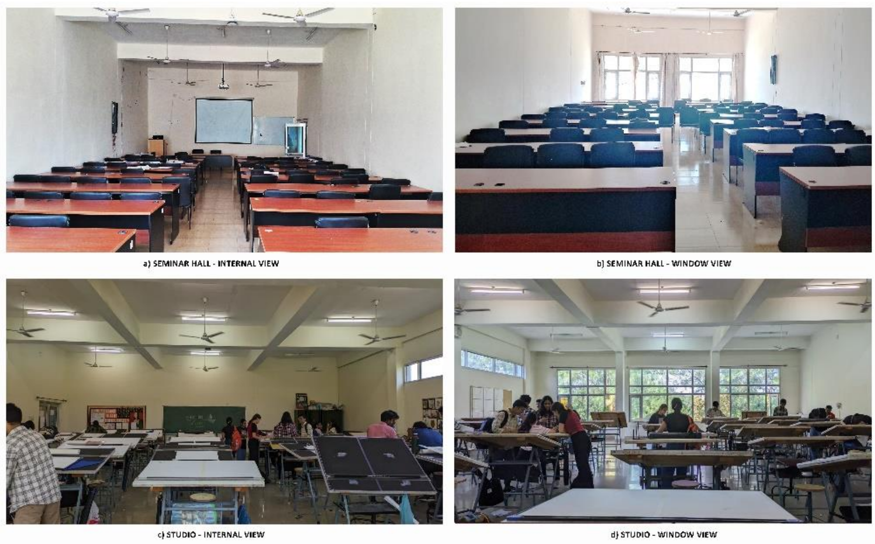

Figure 4. Built Environments: Interior of Seminar Hall and Studio (Source: Author).

2.5. Brainwave and cognitive data acquisition and processing

To facilitate the experimental protocol, each participant had to wear a mobile electroencephalography (mEEG) device namely the InterAxon Muse S, while sitting in the designated learning environment. The Muse S, an EEG device of research-grade quality developed by Interaxon, serves as the apparatus employed for the acquisition of brainwave data in this study.

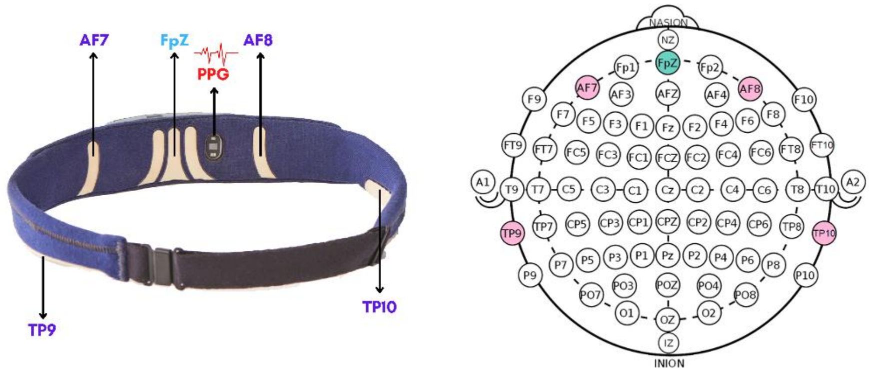

Figure 5. Interaxon Muse S EEG device with electrodes marked (left) and their location as per EEG 10–20 international system (right) (Source: Author).

This device is equipped with four dry electrodes strategically positioned at AF7, AF8, TP9, and TP10 locations as per the EEG 10-20 system, facilitating the collection of brainwave signals encompassing alpha, beta, gamma, theta, and delta frequencies from the frontal and temporal nodes of the brain. The Muse S through its distinctive use in various multidisciplinary studies, thus stands as a reliable instrument for the precise and comprehensive recording of electroencephalographic activity for the course of this study (Domjan et al., 2023; Mansi et al., 2022; Cannard et al., 2021; Mehmood et al., 2023; Asim et al., 2023).

Using a sample rate of 256 Hz, EEG data were captured using the Muse Monitor application and underwent a complex procession through advanced software tools including the extensive EEGLAB toolbox developed by the Swartz Centre for Computational Neuroscience (Delorme & Makeig, 2004). Using MATLAB, we were able to precisely compute the Power Spectral Density (PSD) in each of the standard frequency bands: beta, gamma, alpha, theta, and delta. These bands provide information on different cerebral rhythms. A bandpass filter was used to filter through individual brain waves, keeping just the most pertinent frequencies. After this filtration, the complicated multivariate EEG signals were broken down into their independent components using the Independent Component Analysis (ICA) technique. The last step in this data curation process was a careful cleaning, where any segments that were contaminated by electrical noise or poor electrode performance were removed. This ensured that the EEG data would remain clear and intact for further analysis. Topographic maps, often known as headplots or topoplots, were created for each participant's EEG data to allow for a visual evaluation of the FAA conditions.

The Frontal Alpha Asymmetry (FAA) indices were calculated by taking the natural logarithm of the alpha power at the right frontal electrode (AF8) and subtracting the natural logarithm of the alpha power at the left frontal electrode (AF7) as shown in the following equation (Koslov et al., 2011; Reznik & Allen, 2018; Zhang et al., 2018):

$$FAA = \ln(AF8) - \ln(AF7)$$

The experimental procedure was conducted with individual participants, ensuring that each subject experienced both learning environments—studio and seminar hall—in a randomized order. This approach allowed for the repeated application of the protocol depicted in figure 6 for each environment, aiming to minimize order effects and ensure unbiased comparisons between the two settings.

As depicted in Fig. 6 showcasing graphical protocol of the study, to assess the initial mood and cognitive state of participants, the valence arousal test was employed before the experimental baseline and cognitive sessions began. This step was crucial for identifying mood outliers and ensuring the reliability of subsequent cognitive test results. Baseline measurements were then established, serving as a reference point for normalizing data collected during the study. This methodological sequence was designed to provide clean, normalized data for analysis, reflecting the study's meticulous approach to examining the impact of biophilic design elements on learning environments. In a structured sequence, participants were directed to maintain an open-eyed observation of the spatial surroundings for an initial duration of one and a half minutes. The duration of 180 seconds (3 minutes) for environmental stimuli has been previously established as valid in an EEG study conducted by Herman et al., 2021. This period was preceded by an equivalent timeframe during which participants closed their eyes, allowing for an introspective phase. This cyclical process was instrumental in the development of individual baseline brainwave patterns over the cumulative span of three minutes.

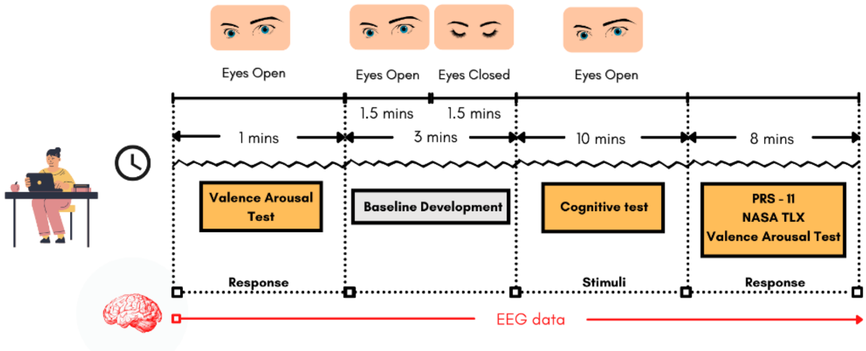

Figure 6. Graphical protocol of the study (Source: Author).

The study commenced with the administration of a combination of cognitive assessments to the participants. These assessments include the Benton Visual Retention Test (BVRT), Digit Span and Backward Digit Span Test (DST/BDST), Stroop Test (ST), and Digit Symbol Substitution Test (DSST) (Lim et al., 2013). The BVRT involved presenting participants with an image for a duration of 10 seconds, after which they were provided with four response options. This test specifically evaluated the visual perception and visual memory capabilities of the participants (Benton at el., 1946). The Digit Span and Backward Digit Span Test focused on assessing the attention and memory functions of the participants. A series of numbers appeared sequentially on the screen, requiring participants to memorize and subsequently reproduce the sequence in both forward (Digit Span) and reverse (Backward Digit Span Test) orders (Jones et al., 2015). The Stroop Test targeted executive function and attention where the participants were tasked with 'speaking' the ink colour of words presented on the screen, aiming to minimize the influence of the actual word on their responses. The imperative was to respond swiftly while maintaining accuracy (Stroop et al., 1935). The Digit Symbol Substitution Test was conducted in a pen-and-paper format where the participants were allocated a symbol corresponding to each digit and were instructed to transcribe the symbols beneath their respective digits within a stipulated time limit of one and a half minutes. This particular test gauged the perceptual abilities of the participants (McLeod et al., 1982). The participants were familiarised with the cognitive tests prior to the experiment. The scores from all cognitive tests were normalized as it ensures scale consistency across different parameters, enhancing the precision and effectiveness of the computations that follow (Hancock et al., 1988; Singh & Singh, 2020).

In the current study, both the PRS and NASA-TLX instruments have been employed to gauge the restorative experiences and cognitive load experienced by participants within the learning-built environment while engaging in cognitive tests. This integrated approach allows for a nuanced understanding of the interplay between the environmental attributes, cognitive demands, and the subjective experiences of individuals within the educational context. Additionally, they engaged in the assessment of emotional states using the valence-arousal model of emotions. Fig. 7 depicts the entire EEG data acquisition, processing, and feature extraction along with cognitive, perception and environmental data collection procedure.

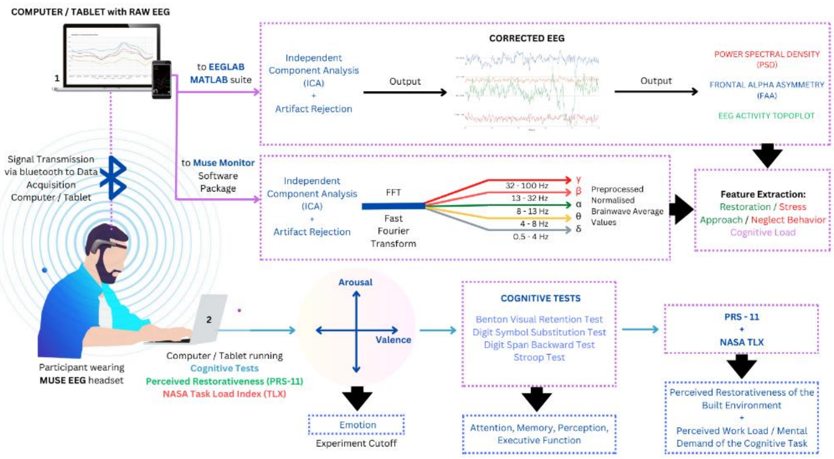

Figure 7. EEG data acquisition, processing, and feature extraction along with cognitive, perception and environmental data collection (Source: Author).
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2.6. Statistical analysis

The statistical analysis was conducted utilizing IBM® SPSS® Statistics Version Amos 27.0. Descriptive statistics, such as frequencies and percentages, characterized categorical variables, while continuous variables, accounting for psychophysiological traits, were summarized using means and standard deviations. A suite of analytical techniques, comprising Chi-square and ANOVA were deployed to investigate varied combinations of continuous and categorical variables within the analytical framework. The visual representation of the diverse associations under examination, inclusive of appropriate statistical methodologies, is delineated in Fig. 2.

3. Results

The comparison of data from the Seminar Hall and Studio learning environments which is tabulated in Table 3 reveal how different surroundings might affect brainwave activity and cognitive ability. As shown in Fig. 8, Delta, Theta, and Gamma waves had somewhat higher mean values in Seminar Hall. This pattern suggests that the Seminar Hall setting promotes relaxation and meditation, as seen by the presence of Delta and Theta waves, which are frequently linked with profound relaxation and the early stages of sleep. Results from Studio revealed a significant increase in Alpha wave activity and a little increase in Beta wave activity. This might suggest that the Studio atmosphere promotes a state of relaxed alertness, which is ideal for creative and cognitive pursuits, as Alpha waves relate to relaxed mental states and Beta waves with active, engaged thinking.

The Studio environment outperformed the Seminar Hall on all cognitive tests (nBVRT, nDST, nBDST, nST, and nDSST), as indicated by far better mean scores as depicted in Fig. 9. This shows a direct link between the environment and cognitive capabilities such as memory, attention, and problem-solving skills. The cognitive score, which is a cumulative score of all five cognitive tests, was much higher in the Studio (as shown in Table 3), supporting the theory that the Studio's biophilic-influenced spatial and environmental qualities are more conducive to cognitive activities and mental agility.

In the Studio, the mean PRS-11 score is higher (46.32) than in the Seminar Hall (36.18). This implies that participants thought the Studio was typically more reviving or restorative than the Seminar Hall. Compared to the Seminar Hall (26-61, Std. Dev. = 7.48), the Studio has a larger range and standard deviation (21-60, Std. Dev. = 11.42). This suggests that participants' perceptions of the Studio's restorative qualities varied more than expected, with some perceiving it as very restorative and others as less so. In the Studio, the mean NASA-TLX score is higher (56.65) than in the Seminar Hall (50.65). This suggests that people perceived that the tasks completed in the Studio were more difficult or stressful. The NASA-TLX score's range and standard deviation are also larger in the Studio (42 to 80, Std. Dev. = 10.48) than in the Seminar Hall (40 to 75, Std. Dev. = 8.44), indicating that there was greater variation in the Studio about how difficult the tasks were viewed to be. Interestingly, the Studio had a greater perceived workload (NASA-TLX) even though it was thought to be more restorative (PRS-11). This might mean that even while the Studio setting is better for restoration, the work done there may be more difficult or need a higher level of cognitive involvement.

		SEMINAR HALL – less biophilic				***STUDIO – more biophilic***			
		Mean	***Min.***	***Max.***	***Std. Dev.***	***Mean***	***Min.***	***Max.***	***Std. Dev.***
Brainwaves	***Delta***	.252	.160	.390	.062	.218	.080	.320	.062
	Theta	.174	.127	.220	.025	.164	.129	.230	.029
	Alpha	.217	.170	.280	.024	.274	.189	.370	.050
	Beta	.222	.144	.310	.042	.217	.130	.300	.044
	Gamma	.135	.064	.210	.036	.128	.060	.220	.036
Cognitive Tests	***nBVRT***	.364	.000	1.000	.289	.636	.000	1.000	.307
	nDST	.318	.000	0.750	.221	.648	.000	1.000	.263
	nBDST	.273	.000	1.000	.266	.648	.250	1.000	.295
	nST	.568	.000	0.950	.231	.426	.000	1.000	.221
	nDSST	.487	.000	0.900	.246	.732	.500	1.000	.157
	Cognitive Score	2.010	.754	3.342	.655	3.090	1.736	4.052	.710
	PRS-11	36.18	26	61	7.48	46.32	21	60	11.42
	NASA-TLX	50.65	40	75	8.44	56.65	42	80	10.48
FAA	***Right***	12				3			
	Left	11				19			

Table 3. Descriptive statistics of the Brainwave and Cognitive Tests in different learning environments.

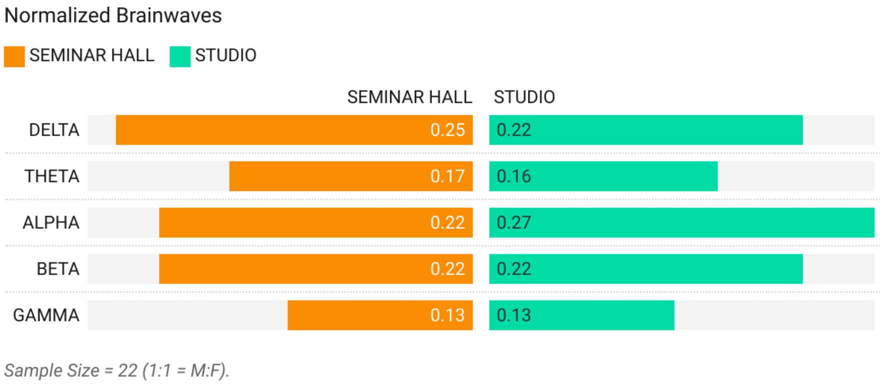

Figure 8. Comparative Analysis of Normalized Brainwave in Seminar Hall and Studio: This chart presents the mean values of different brainwave types (Delta, Theta, Alpha, Beta, Gamma) measured in the Seminar Hall and Studio (Source: Author).

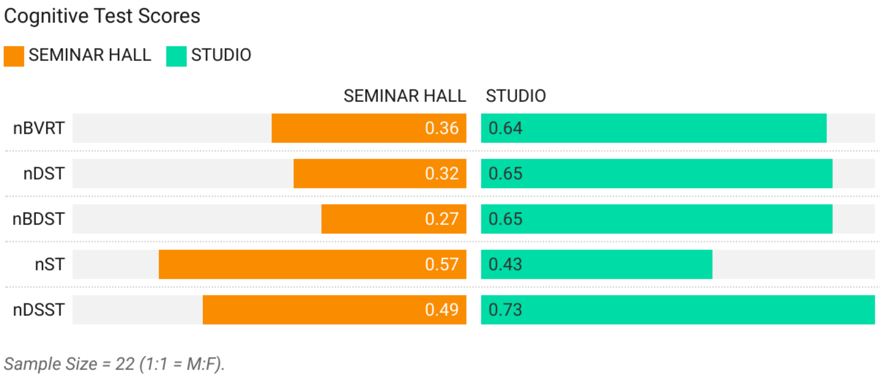

Figure 9. Comparative Analysis of normalized Cognitive Test Scores in Seminar Hall and Studio: This chart illustrates the mean scores of various cognitive tests (nBVRT, nDST, nBDST, nST, nDSST) conducted in the Seminar Hall and the Studio (Source: Author).

Comparative EEG Alpha Band (~10Hz) Topoplots for Participants 1-11 (Female) and 12-22 (Male) in Non-Biophilic (Seminar Hall) and Biophilic (Studio) Environments are shown in Fig. 10. Topoplots employ a colour scale of -4 µV to +4 µV. Cooler colours (blues) imply lower electrical potential, but warmer colours (reds and yellows) suggest greater electrical potential. Certain parts of the brain show more activity (warmer colours) in one setting compared to another, indicating a persistent pattern. This shows that the two contexts differ in terms of brain activation or relaxation. The brain activity is not seen to be distributed evenly throughout the scalp. There are localized fluctuations in activity, which might imply that specific cognitive processes or emotional states are more prominent in one context than the other. Different patterns of brain activity might indicate different cognitive and emotional states. For example, more frontal activity is frequently connected with engagement and attention, but higher occipital activity may be related to visual processing. Hypothesis H1a and H1b in the next segment will analyze the influence of different built environments on the electrical activity in the brain.

3.1. Frontal Alpha Asymmetry (FAA)

H1a

The analysis involved a Chi-square test to examine the association between Frontal Alpha Asymmetry (FAA) and the type of built environment (Seminar Hall vs. Studio). The results of the Chi-square test demonstrate a significant association between Frontal Alpha Asymmetry (FAA) and the type of built environment ($\chi^2 = 12.239$, df = 1, $p < 0.001$). Putting both hypothesis H1a and Fig. 10 comparative topoplots of the participants into consideration, out of the total 30 left aligned FAA (detailed in Table 3), studio learning environment exhibited more left aligned FAA results (19/30) as compared to seminar hall (11/30). This finding suggests that there is a relationship between the asymmetry in frontal brain activity and the specific architectural setting, indicating potential cognitive variations based on the biophilic presence in the learning built environment.

3.2. Normalized Alpha (a) Brainwave

H1b

The null hypothesis, positing no difference between groups, is emphatically rejected based on the results of the ANOVA and a statistically significant difference between groups is observed, predicated on the alpha. The F-statistic, registering at 23.010, signifies a substantial effect. This implies that the variability between groups far exceeds the variability within groups. The p-value, being less than 0.001, furnishes robust evidence against the null hypothesis, bolstering the case for a significant difference between groups. The sum of squares between groups (0.036) is comparatively modest in relation to the total sum of squares (0.102). This implies that the groups elucidate a substantial proportion of the

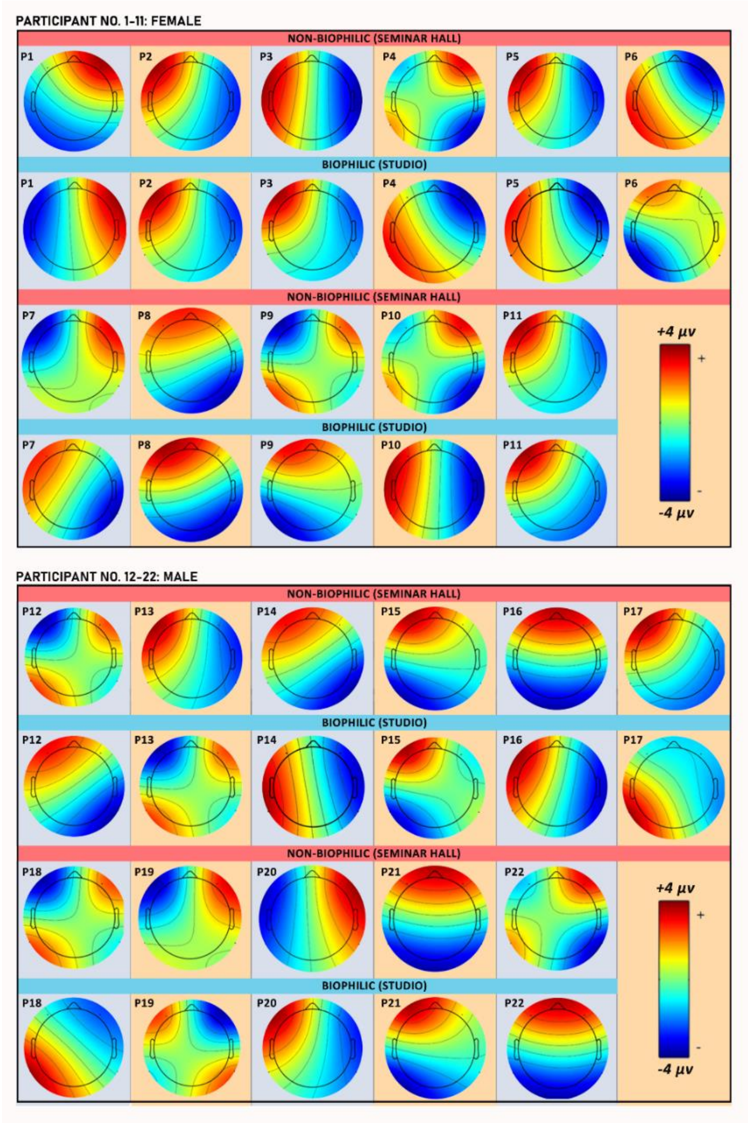

Figure 10. Comparative EEG Alpha Band (~10Hz) Topoplots for Participants 1-11 (Female) and 12-22 (Male) in Non-Biophilic (Seminar Hall) and Biophilic (Studio) Environments. (Each topoplot represents the mean alpha power distribution, measured in microvolts (µV), across the scalp with +4 µV indicating higher alpha activity and -4 µV indicating lower alpha activity. This visualization captures the contrast in brainwave patterns between the two different environmental contexts for each participant) (Source: Author).

variance in alpha. Thus, the results of the ANOVA underscore a statistically significant dissimilarity between groups, as evidenced by alpha. The effect size is considerable, suggesting that the observed differences are not mere chance occurrences. These findings contribute to a nuanced understanding of the impact of group variations on alpha, reinforcing the empirical robustness of the study outcomes.

3.3. PRS-11 and NASA-TLX

H2a

The null hypothesis, positing no difference between groups, is decisively rejected and a statistically significant difference between groups is affirmed based on the PRS-11 variable ($p = 0.001$). The F-statistic, measuring at 12.134, denotes a moderate to large effect size. This implies that the observed variability between groups is considerable. The sum of squares between groups (1130.205) is substantially relative to the total sum of squares (5042.250). This indicates that the groups elucidate a significant proportion of the variance in the PRS-11 variable.

H3a

The null hypothesis of no difference between groups is rejected for the NASA-TLX variable. A statistically significant difference between groups is identified based on the NASA-TLX variable ($p = 0.043$). The F-statistic stands at 4.374, suggesting a moderate effect size. This implies that the variability observed between groups is of moderate magnitude. The sum of squares between groups (396.020) is moderate compared to the total sum of squares (4199.103). This suggests that the groups explain a moderate proportion of the variance in the NASA-TLX variable.

The ANOVA results for both PRS-11 and NASA-TLX variables reveal statistically significant differences between groups, underscoring the impact of the built environment on participants' experiences. Effect sizes further indicate the magnitude of these differences, with PRS-11 exhibiting a moderate to large effect, and NASA-TLX reflecting a moderate effect. The substantial proportions of variance explained emphasize the influential role of the built environment in shaping participants' perceptions and workload.

3.4. Cognitive Score

H4a

The ANOVA results shown in Table 4 underscore the substantial impact of the built environment on participants' cognitive performance across various tests. All p-values ($p < 0.05$) indicate statistically significant differences, emphasizing the influence of the built environment on cognitive outcomes. Notably, the Cognitive Score exhibits a substantial F-statistic of 27.508, underscoring the robust effect size and highlighting the pronounced impact of the built environment on overall cognitive performance.

ANOVA						
		Sum of Squares	*df*	*Mean Square*	*F*	*Sig.*
BVRT	Between Groups	.818	1	.818	9.195	.004**
	Within Groups	3.737	42	.089		
	Total	4.556	43			
DST	Between Groups	1.195	1	1.195	20.230	.000**
	Within Groups	2.480	42	.059		
	Total	3.675	43			
BDST	Between Groups	1.547	1	1.547	19.563	.000**
	Within Groups	3.321	42	.079		
	Total	4.868	43			
ST	Between Groups	.220	1	.220	4.319	.044*
	Within Groups	2.142	42	.051		
	Total	2.362	43			
DSST	Between Groups	.658	1	.658	15.400	.000**
	Within Groups	1.795	42	.043		
	Total	2.453	43			
Cognitive Score	Between Groups	12.839	1	12.839	27.508	.000**
	Within Groups	19.603	42	.467		
	Total	32.442	43			
*p<0.05, **p<0.01						

Table 4. ANOVA results of Cognitive Tests and Built Environment.

4. Discussion

This study presents an innovative analysis into the cognitive benefits of biophilic learning settings using an EEG-based approach, adding to a more nuanced understanding of the relationship between architecture and cognitive performance (Jung et al., 2023). These findings support the idea that biophilic features in educational settings improve cognitive performance significantly, which is consistent with the theoretical frameworks of Attention Restoration Theory (ART) and Stress Reduction Theory (SRT).

First, the observed improvements in FAA in ‘more biophilic’ learning environment supports the notion that natural elements in learning spaces positively influence emotional well-being and cognitive preparedness. This is consistent with prior research indicating that exposure to natural environments promotes a state of mental restoration, which is important for cognitive processes like attention and memory (Kaplan et al., 1989). The results of this study align with and strengthen existing research findings, underlining the importance of biophilic design in establishing ideal learning environments. More importantly, the enhanced Normalised Alpha brainwave activity reported in ‘more biophilic’ learning settings supports the restorative effect of these environments. This is in accordance with the findings of Ulrich et al., 1991, who hypothesised that natural surroundings reduce stress and increase psychological well-being. This study adds to this understanding by quantifying the cognitive benefits using EEG measures, providing empirical data to justify the use of biophilic components in educational architecture.

The results of the NASA Task Load Index (NASA-TLX) and the Perceived Restorativeness Scale (PRS-11) reinforce the cognitive benefits of biophilic surroundings. Higher levels of perceived restorativeness are shown by the substantial difference in PRS-11 scores between biophilic and non-biophilic situations. This is important since sustained cognitive engagement and performance depend on these levels. Additionally, the study's methodology—which uses EEG to detect cognitive responses directly—represents a substantial leap in the fields of both built environment and environmental psychology research. It provides a more thorough knowledge of the influence of built environments on cognitive processes by bridging the gap between subjective impressions and objective cognitive performance indicators. This research concludes by highlighting how crucial it is to use biophilic design components in learning environments in order to promote the best possible cognitive functioning. It gives architectural decisions a scientific foundation and emphasises the requirement of designing learning settings that are not only practical but also advantageous to the brain.

4.1. *Scope and limitations*

This study on the cognitive benefits of biophilic learning environments, while insightful, has certain limitations that warrant consideration for future research.

The restricted number of participants in this study may have an impact on how broadly applicable the results are. Furthermore, the uniform demographic and educational background of the sample may restrict the generalizability of the findings to other groups. Expanding and diversifying the participant groups in future research endeavours will improve the external validity of the results. Additionally, a 4 electrode EEG system was chosen for its portability and suitability for non-laboratory research. While this system facilitates the study of cognitive responses in real-world environments, it inherently provides EEG data with reduced spatial resolution. This limitation is significant, as it impacts the level of detail in the acquired brain activity data. Despite this, we have employed robust statistical methods to ensure that the insights derived from our analysis remain meaningful. Our methodology section elaborates on how the study's design compensates for these limitations, aiming to balance ecological validity with the depth of cognitive insights obtained. Because this study is cross-sectional, it only provides a fleeting image of how biophilic situations affect people. Research with a longitudinal design is required to comprehend the long-term effects. The study's learning environments differed in several aspects beyond the intended "biophilic" level, including variations in desk arrangements, room dimensions, and available equipment. This recognition highlights the complexity of isolating biophilic elements as the sole factor influencing the observed outcomes. These environmental differences could potentially affect the study's findings, making it challenging to attribute observed differences in participant responses directly and solely to the biophilic design elements. This acknowledgment serves to underline the multifaceted nature of learning environments and their impact on cognitive and emotional responses, stressing the necessity for further research aimed at isolating and assessing the specific contributions of individual design elements within educational settings.

5. Conclusions

The present research represents a significant progression in comprehending the cognitive effects of nature induced / biophilic learning environments. We have experimentally shown that the integration of natural components in educational settings may improve cognitive function, as indicated by changes in Frontal Alpha Asymmetry and Normalised Alpha brainwave activity. This has been accomplished through innovative utilisation of EEG equipment along with a set of perception-based questionnaires. These results demonstrate that biophilic design is not only an aesthetic decision but an essential element in creating the best possible learning environment. They also support and expand upon the theoretical foundations of Attention Restoration Theory and Stress Reduction Theory.

According to our study, biophilic spaces can facilitate better emotional health and cognitive preparedness, both of which are essential in learning environments. The NASA Task Load Index indicates a considerable reduction in cognitive load and a significant increase in Perceived Restorativeness Scale scores. These findings highlight the tangible benefits of these settings in terms of stress reduction and improved ability to participate in sustained cognitive activity. Still, this study's implications are not limited to academic environments. The results have wider implications for environmental and architectural design, since they imply that biophilic design components may be intentionally used to improve cognitive performance in a variety of settings, including public spaces and workplaces. Given these results, it is advised that biophilic design components be included into educational and other spaces by educators, architects, and policymakers in order to support cognitive and emotional well-being. It is important that future studies build on these findings by investigating a range of contexts and long-term effects. In conclusion, this study adds an essential component to our understanding of the intersection between environment and cognitive performance. It emphasises how advanced techniques like EEG can be used in tandem with biophilic design to further understand and develop settings that are not only helpful for learning but also play a key role in improving cognitive functions that are essential for academic achievement.

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Ethics statement

The study protocol was approved by the institutional review board at NIT Hamirpur (NIT/HMR/Acad./Ph.D./05/Sup./2023/234–235), and informed consent was obtained from each participant prior to the start of study.

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