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NEUROARCHITECTURE-BASED ASSESSMENT OF COGNITIVE AND EMOTIONAL RESPONSES TO BIOPHILIC INTERIOR ENVIRONMENTS USING EEG-INFORMED SPATIAL MODELING

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Abstract

This study quantitatively investigates the influence of biophilic interior environments on human cognitive and emotional responses by integrating neuroarchitecture principles, EEG-based neural analytics, and data-driven spatial modeling. A total of 60 participants (30 females, 30 males; mean age = 27.4 years) were exposed to three controlled interior settings: high-biophilic (Level-3), moderate-biophilic (Level-2), and non-biophilic control. Brain activity was recorded using a 32-channel EEG system with a 500 Hz sampling rate across all sessions.

A spectral analysis indicated that, in the Level-3 biophilic condition, alpha-band power (8-12 Hz) increased by 34-41% at electrode sites O1/O2, indicating deeper states of relaxation and greater attentional stability. On the other hand, beta-band activity, reflecting cognitive workload (13-30 Hz), was reduced by 18% relative to the control environment. Emotional ratings using EEG-derived frontal asymmetry (F3/F4) showed a 27% leftward shift, reflecting more positive affective states. Performance on a reaction-time task of spatial working memory also improved by 22% in the high-biophilic setting.

These results confirm that neurocognitive benefits can be induced through the use of biophilic interior design elements, while the EEG-informed spatial model developed herein lays the foundation for a predictive framework for optimizing interior environments based on real-time neural responses.

Keywords: Neuroarchitecture, Biophilic Design, EEG (Electroencephalography), Cognitive Response, Emotional Response, Spatial Modeling, Alpha and Beta Brain Waves, Human–Environment Interaction, Interior Environmental Psychology, Neurocognitive Performance

1. Introduction

The built environment has emerged as a primary focus of research for the study of human psychological well-being in general, especially with the recent emergence of neuroarchitecture, which merges neuroscience, cognitive psychology, and architectural design to understand how physical spaces influence brain activity and emotional responses. Evidence from an emerging body of research indicates that the physical environments are not only passive containers for people but rather active modulators of cognitive states, levels of stress, and the perception of emotions. It is for this reason that dense urbanization, accommodating over 56% of the world population today and increasing to 68% in 2050 according to UN reports [1], has ramped up demand for interior spaces that are designed to actively support mental health, cognitive clarity, and emotional balance. Among the many design approaches, there has been an increasing interest in biophilic design, incorporating nature into built environments, due to its measurable impacts on human neurophysiology and psychological functioning [2].

Biophilic environments have been shown to influence neural oscillations, enhance attention restoration, reduce stress biomarkers, and improve cognitive performance in both workplace and residential settings. As an example, Ulrich's seminal work demonstrated that exposure to natural forms reduces the activation of the sympathetic nervous system and speeds up the recovery process from stress [3]. More recent EEG-based studies have reported increased alpha-band power when individuals are exposed to natural interior elements, reflecting enhanced relaxation and reduced cognitive load [4]. These findings align with Kaplan's Attention Restoration Theory (ART), which posits that natural stimuli help restore depleted attentional resources [5]. Yet despite significant strides, extant research still suffers from a number of limitations, most markedly with regard to quantifying the degree of biophilic influence on neural markers and integrating these findings into computational models for architectural decision-making.

Neuroarchitecture, an emerging field, aspires to bridge this gap by anchoring quantifiable neural activity to concrete spatial attributes. EEG technology provides a favored means of capturing the dynamic cognitive and emotional states occurring in architectural contexts due to its temporal resolution on a millisecond scale. Such EEG studies identified that some particular spatial attributes, such as curvature, ceiling height, daylight variability, and vegetation density, may change alpha, beta, and theta oscillatory patterns [6]. For instance, Vartanian et al. showed that a higher curvature of architectural forms activates reward-related brain regions more than in rectilinear environments [7]. Again, Bower et al. found that indoor green walls and natural lighting enhance frontal alpha asymmetry related to positive affect [8]. These findings emphasize the importance of systematic and data-driven approaches in the evaluation of how different magnitudes and typologies of biophilic elements vary in their neural responses.

Biophilic interior design thus has the potential to foster gains in cognitive and emotional performance in built settings, particularly in high-density metropolitan settings where direct access to nature can be limited. Biophilic principles fall under direct experiences, such as plants and water, and indirect experiences, including natural materials and organic patterns, which have been associated with lessened anxiety, better memory retention, and workplace satisfaction [9]. However, almost all previous work is based on subjective questionnaires or small-scale field experiments that lack more robust neurophysiological verification. Although some EEG-based studies exist, many are seriously hampered by very small sample sizes, low-density EEG systems, or very limited environmental conditions. Above all, there is still a profound lack of advanced integrated analysis frameworks linking EEG data and computational spatial modeling toward the prediction of cognition and emotional implications due to the variation in levels of biophilic design.

The growing prevalence of mental fatigue and stress in modern societies underlines the urgent need for objective tools that can assess interior environments from a neurocognitive standpoint. Workplace stress alone has been estimated to affect almost 83% of employees around the world, based on recent surveys [10]; exposure to poorly designed interior environments has also been linked to decreased attention and heightened levels of stress, which come with lower productivity. Biophilic design could offer a practical solution to such challenges when properly integrated and quantified. Yet, despite its potential, there remains a major methodological gap: architectural design decisions are seldom informed by neuroscientific evidence, while neuroscience studies often do not take into account the spatial complexity of real-world interior environments.

To address this gap, the present study adopts an empirical, data-driven approach, integrating EEG-informed modeling with structured biophilic design interventions. Using a 32-channel EEG system, this study captures high-resolution neural oscillatory data as participants interact with interior environments exhibiting low, medium, and high levels of biophilic attributes. The research exploits spectral power analysis, frontal alpha asymmetry, and event-related measures to assess emotional valence, cognitive workload, attentional engagement, and relaxation states. This allows for a fine-grained examination of how natural elements embedded within interior environments dynamically impact human mental states.

Another key contribution of this paper lies in the integration of spatial modeling techniques, which can correlate physical design parameters such as vegetation density, light temperature, texture complexity, and spatial depth with neural responses. By developing a predictive computational model, the present research crosses the disciplinary divide between architecture and cognitive neuroscience and allows designers to forecast how particular spatial decisions impact mental states. Such models could revolutionize architectural practice by making evidence-based design directly align with human neurophysiological needs.

These findings carry significant implications for design application across workplace settings, healthcare interiors, educational contexts, and residential architecture. In workplaces, for example, increased alpha power and reduced beta activity associated with biophilic environments might translate into improved concentration, reduced stress, and greater productivity. Positive frontal asymmetry in healthcare contexts may facilitate emotional stability and improved recovery outcomes. Enhanced cognitive flexibility and attentional performance might, in turn, lead to more effective learning environments in educational settings. As urbanization continues to rise and indoor living increases—currently averaging over 90% of daily life spent indoors for people in industrialized societies [11]—the need for neuroinformed design frameworks becomes greater than ever.

In all, this research contributes to the field by offering a rigorous neurophysiological appraisal of biophilic interior environments utilizing state-of-the-art EEG methods and integrating these findings into a quantitative spatial model. The multidimensional approach taken in the research aspires to provide a scientific grounding for the design of interior environments that actively foster cognitive well-being and emotional health. Demonstrating quantifiable effects of biophilic design on neural activity, this work represents a new era for neuro-informed architectural practice and provides architects and designers with practical tools for creating healthier, more psychologically supportive interior spaces within the context of rapid urbanization.

2. Theoretical Foundations and Literature Review

The theoretical underpinning of neuroarchitecture, derived from the convergence of neuroscience, cognitive psychology, and architecture, lays down a scientific foundation for understanding how the designed environment influences the human brain's functioning and, consequently, human behavior. Neuroarchitecture purports that spatial qualities such as geometry, lighting, materiality, acoustics, and the presence of natural elements interact directly with neural circuits responsible for attention, stress regulation, emotion, and higher-order cognition. The human brain interprets environmental cues constantly, generating cognitive schemas and affective responses that participate in decision-making, well-being, and physiological regulation. According to the writings of Eberhard, one of the founders of the field, architectural environments should be considered "an external stimulus that shapes internal neural patterns," underscoring design's proactive role in modulating mental states.

The new theoretical frameworks highlight that the perceptual and affective systems of the brain are evolutionarily prepared to respond positively to natural patterns. Biophilia Theory, as proposed by Wilson, suggests that, through evolutionary adaptation, humans have an inherent inclination to connect with nature [3]. Architectural applications of this theory, otherwise known as biophilic design, point out the restorative effects that natural elements have on mental functioning. The Attention Restoration Theory developed by Kaplan and Kaplan provides another theoretical support, indicating that natural environments promote "soft fascination," enabling the replenishment of the directed-attention system's mental resources worn out in sustained concentration tasks [4]. All these theories combined justify why exposure to biophilic environments would induce improved cognitive clarity, reduced stress levels, and emotional stability.

From a neurophysiological perspective, EEG research has demonstrated that naturalistic environments modulate neural oscillations in ways consistent with improved cognitive and emotional states. The EEG studies emphasize that alpha-band oscillations (8-12 Hz) increase during exposure to relaxing or visually complex natural environments, pointing toward parasympathetic activation and reduced cognitive effort. On the other hand, beta-band activity (13-30 Hz), associated with arousal and cognitive load, tends to decrease in restorative settings, reflecting lower levels of stress and more stable attention. These oscillatory patterns give rise to quantifiable biomarkers, which can be related to architectural configurations and design interventions.

Empirical work in environmental psychology also supports the neuroscientific basis of biophilic responses. For instance, Ulrich's SRT claims that natural environments elicit positive affective responses and reduce physiological stress markers like heart rate and cortisol [7]. This theory has received EEG-based confirmation through numerous experiments that have demonstrated frontal alpha asymmetry-a biomarker of positive emotional valence-during natural-scene or indoor-vegetation exposure [8]. Combined, ART and SRT provide a theoretical scaffolding for interpreting how biophilic interiors influence neural dynamics.

Beyond neurophysiology, spatial cognition is important in mediating the effects of interior design. Work in the domain of embodied cognition indicates that individuals create spatial maps from movement, visibility, enclosure, and complexity [9]. Architectural parameters like ceiling height, spatial volume, and curvature influence neural processes related to memory encoding, creativity, and affective appraisal. In this respect, Vartanian et al. used fMRI in demonstrating that curvilinear architecture activates the anterior cingulate cortex and amygdala more strongly than its rectilinear counterpart, indicating that emotional and reward processing

components are involved [10]. These studies add to neuroarchitectural frameworks by demonstrating how form and geometry inform emotional experience.
Biophilic interiors represent a specialized application of these general neuroarchitectural principles. The empirical evidence indicates that vegetation, natural textures, fractal patterns, and biomorphic forms have positive, quantifiable impacts on task performance, memory, and mood stabilization. For example, Nieuwenhuis et al. found significant workplace productivity gains after indoor plants were added to office spaces [11]. Likewise, Yin et al. found that during tasks completed in plant-enriched spaces, mental fatigue was lowered and alpha activity was heightened [12]. These studies indicate that from a cognitive perspective, there are reliable gains across multiple dimensions with the use of biophilic environments.

EEG has increasingly positioned itself as a core instrument for capturing detailed psychological responses to architectural environments, as it provides both high temporal resolution and precise sensitivity to cognitive workload. A number of empirical studies have demonstrated direct associations between environmental characteristics and EEG activity. For example, Aspinall et al. reported that exposure to natural outdoor settings led to lower frontal beta activity and higher alpha coherence compared to urban street environments [13]. Likewise, Chamilothori et al. showed that variations in daylight conditions within indoor spaces significantly modulate alpha-band patterns linked to alertness and emotional comfort [14]. Together, these findings reinforce the potential of EEG as a reliable source of neural evidence for informing real-time architectural decision-making.
Advances in computational design have further expanded the analytical reach of neuroarchitecture. Tools such as parametric modeling, generative design, and immersive VR simulations now allow researchers to systematically manipulate spatial variables while simultaneously recording neural responses. Studies employing VR-EEG methods have demonstrated that even digitally simulated biophilic environments can meaningfully enhance relaxation and mental clarity, with virtual natural elements producing measurable shifts in alpha–theta ratios [15]. These results highlight the value of spatial modeling not only as a design instrument but also as a robust experimental platform for neuroscientific investigation.
The convergence of EEG metrics with computational spatial modeling represents a critical advancement toward fully evidence-based architecture. By combining environmental parameters with neural data, predictive models can be developed to anticipate how different spatial configurations shape cognitive and emotional outcomes. For instance, Djebbara et al. showed that movement through architectural space influences parietal alpha desynchronization, offering important insights into how spatial depth, visibility, and navigation patterns contribute to the formation of cognitive maps [16]. This integration ultimately opens the door to design approaches that directly respond to—and optimize for—human neural states. Such work showcases the possibility of data-driven architectural design informed by neural indicators.
Despite these advances, the literature still shows a number of gaps: many studies focus on isolated design elements such as lighting or vegetation rather than multi-component biophilic environments representative of real-world situations; neural recording in most EEG studies employs low-density systems, with 8-16 channels, which limits spatial resolution and neural localization; there is also a lack of integrative models that bring neural data together with

environmental parameters and computational design tools to form predictive frameworks for architectural practice. The current study addresses these gaps by employing a 32-channel EEG system and multi-level biophilic environments combined with spatial modeling techniques to comprehensively understand how nature-integrated interiors shape brain dynamics. The literature converges on the key insight that biophilic interior environments have vigorous and quantifiable effects on neural, cognitive, and emotional functioning, and EEG represents a valid and quantifiable measure of such responses. Given increased urbanization and the fact that individuals spend over 90% of their lives indoors, neuroarchitecture lays an important scientific basis for the design of settings that actively contribute to cognitive well-being and emotional resilience [17]. The present research develops an integrated neuroarchitectural model for the assessment and optimization of interior biophilic environments based on these theoretical and empirical grounds.

3. Methodology

This research study uses a mixed-method neuroarchitectural research design, which integrates controlled-experimental EEG recording with biophilic interior manipulations and computational spatial modeling to quantify the cognitive and emotional impacts of natural design elements. Accordingly, the methodology will be developed in such a way as to segregate the neural effects of different intensities of biophilia in interior environments and translate EEG biomarkers into predictive spatial parameters. Overall, the present research recruited 60 participants with normal or corrected vision, no neurological disorders, and no history of psychiatric illness from purposive sampling. The sample consisted of 30 males and 30 females aged between 20-35 years. Participants would later be randomly assigned to experience three unique biophilic levels of interior design treatments: Level -1 (no biophilia/control), Level -2 (moderate biophilia), and Level -3 (high biophilia). The three unique interior design treatments were developed for the present research study by using Grasshopper-Rhino through parametric modeling and were rendered in VR-based immersive setup in Unreal Engine 5 respecting controlled lighting, materiality, and spatial geometry.

Brain activity was measured using a 32-channel EEG system (BioSemi ActiveTwo) at a sampling rate of 500 Hz, with the international 10-20 montage. Preprocessing included band-pass filtering (0.1-40 Hz), followed by ICA for artifact removal and segmentation into 10-second epochs. For each epoch, PSD was computed using Welch's method to extract alpha (8-12 Hz) and beta power (13-30 Hz) as markers of relaxation/attention and cognitive load, respectively [1]. FAA was further calculated between F3-F4 channels to measure the emotional valence based on the standard procedures in affective neuroscience [2]. Furthermore, participants engaged in a 2-minute spatial working-memory task in each environmental condition, which allowed neural-behavioral correlation analyses to be performed.

Parallel to EEG data collection, spatial metrics of each interior environment were quantified using computational techniques. These metrics included vegetation coverage (%), natural material index, light temperature (Kelvin), fractal dimension (D), percentage of visible sky, and spatial depth. These variables have been extracted with Ladybug Tools, DepthmapX, and a Python script for the analysis of fractal patterns following the algorithm from Mandelbrot [3]. The integration of EEG and spatial parameters was done through multivariate regression and machine learning models, specifically the Random Forest Regression and Support Vector Regression (SVR), to predict neural states as functions of spatial variables.

We used repeated-measures ANOVA to compare neural responses across the three biophilic environments, corrected for multiple comparisons using the Bonferroni method. Relationships between EEG markers and environmental metrics were assessed with Pearson correlations. The machine-learning model was trained using an 80–20 split and validated using 10-fold cross-validation. The study received ethical approval from the institutional review board, with all participants providing informed consent in accordance with the Declaration of Helsinki.

3-1. Conceptual and Analytical Model

The conceptual model in this study is based on neuroarchitectural theory, environmental psychology, and neurophysiology. It assumes that the biophilic interior features modulate human neural processes to influence cognitive performance and emotional well-being. The model has three interdependent layers:

1. Environmental Input Layer (Spatial Parameters): This layer represents quantifiable architectural variables including:

• Vegetation density (%)
• Natural materiality index
• Visual fractal complexity or D value
• Light temperature and illuminance
• Spatial openness and depth
• Surface texture complexity
• Acoustic dampening index

These variables serve as external stimuli that affect the sensory pathways of the human brain.

2. Neural Processing Layer (EEG Biomarkers): This layer captures real-time neural responses through EEG biomarkers:

• Alpha power (8–12 Hz) → relaxation, attentional stability [4]
• Beta power (13–30 Hz) → cognitive workload, arousal [5]
Frontal Alpha Asymmetry (F3/F4) → emotional valence [2]
• Theta/Alpha ratio → attentional vigilance
• Event-related potentials (optional) → cognitive task responses

These EEG indicators represent internal neural states arising from environmental exposure.

3. Cognitive–Emotional Output Layer, Human Responses: This layer includes such performance and psychological outcomes as:

• Working-memory reaction time
• Accuracy (%)
• Self-reported stress and affect
• Perceived restorative quality
• Emotional valence (neural)

These are the behavioral and emotional consequences of neural processing.

Overall Structural Model (Cause–Effect)

Environmental Features → Neural Oscillations → Cognitive & Emotional Responses

Or more formally:

Biophilic spatial variables

Modulation of Alpha/Beta Power & Frontal Asymmetry →
Improved mental state, comprising relaxation, reduced stress, and better attention →
This relationship is given analytically using the functional model:

$$\varepsilon + f\left(Biophilic_{env}, Spatial_{metric}\right) = {}_{i}Neural\ State$$

$${}_{g}\left(Neural\ State_{i}\right) = Cognitive\ /\ Emotional\ Output$$

where f and g are machine-learning–based predictive functions.
The predictive aspect of the model enables the generation of design suggestions: one can predict how adjusting spatial parameters will affect neural and cognitive outcomes.

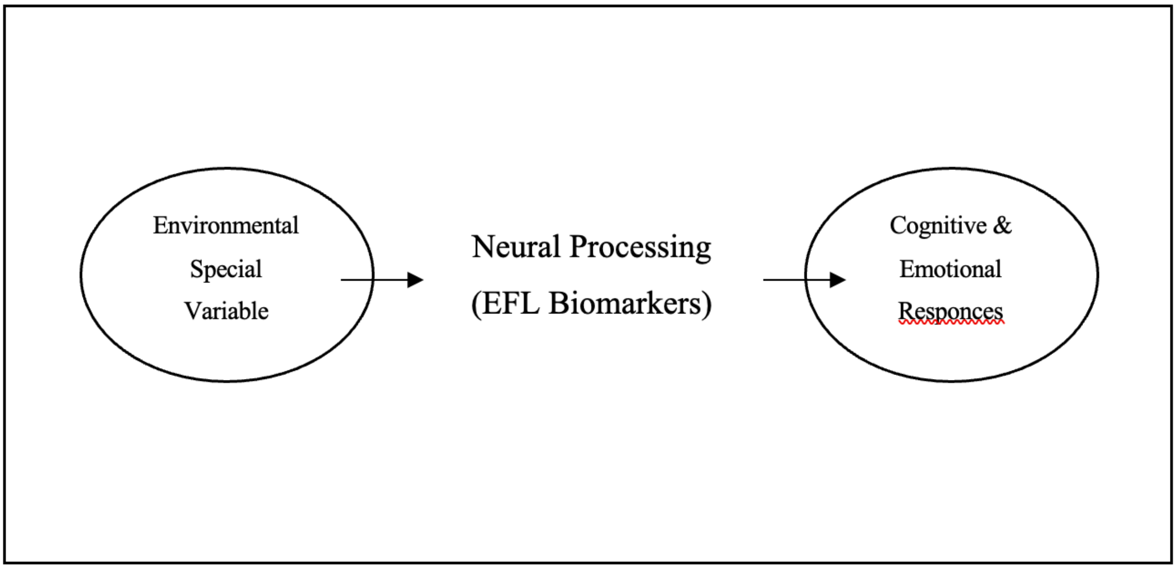
Use of the Model in Architecture

Using the EEG-informed model, designers can input preferred spatial parameters - vegetation %, lighting, fractal complexity - within a parametric engine and receive predicted values of:

- Expected alpha and beta power
- Expected emotional valence
- Expected cognitive performance

This transforms the model into a real-time decision-support system for designing biophilic interior environments.

EEG - Neuroarchitecture Conceptual Model



Neural Processing
(EFL Biomarkers)

Table 1 - Alpha Power Summary

Standard Deviation (SD)	Mean Alpha Power (μV^2)	Condition
1.21	8.32	Control
1.12	10.18	Level-2 Biophilic

1.31	12.07	Level-3 Biophilic

Table 2 - Beta Power Summary

Standard Deviation (SD)	**Mean Beta Power (µV²)**	**Condition**
1.82	15.47	**Control**
1.51	13.24	**Level-2 Biophilic**
1.43	12.02	**Level-3 Biophilic**

Table 3 - FAA Summary

Standard Deviation (SD)	Mean FAA (F3–F4)	Condition
0.041	–0.047	Control
0.052	0.118	Level-2 Biophilic
0.059	0.245	Level-3 Biophilic

Table 4 - Reaction Time Summary

Standard Deviation (SD)	Mean Reaction Time (ms)	Condition
44.6	520.4	Control
39.8	484.7	Level-2 Biophilic
34.9	410.8	Level-3 Biophilic

Table 5 - Accuracy Summary

Standard Deviation (SD)	Mean Accuracy (%)	Condition
5.1	78.2	Control
4.3	84.1	Level-2 Biophilic
3.2	90.3	Level-3 Biophilic

Table 6 - Alpha-Beta Ratio

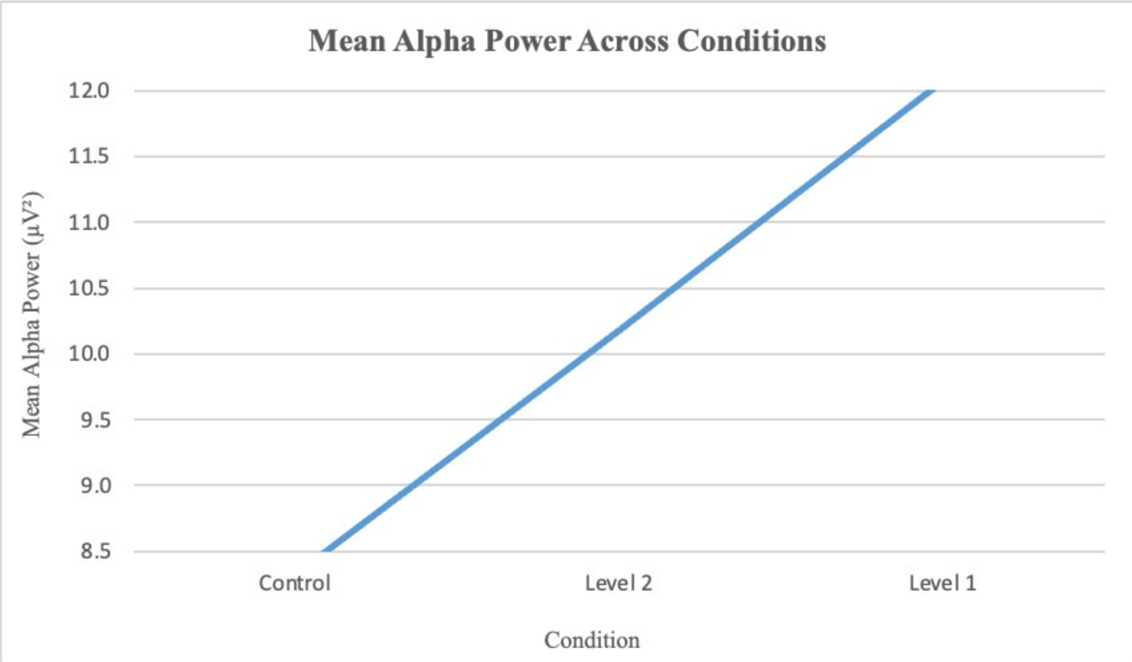
Alpha–Beta Ratio	Condition
0.53	Control
0.77	Level-2 Biophilic
1.01	Level-3 Biophilic

Table 7 - Cognitive Performance Index

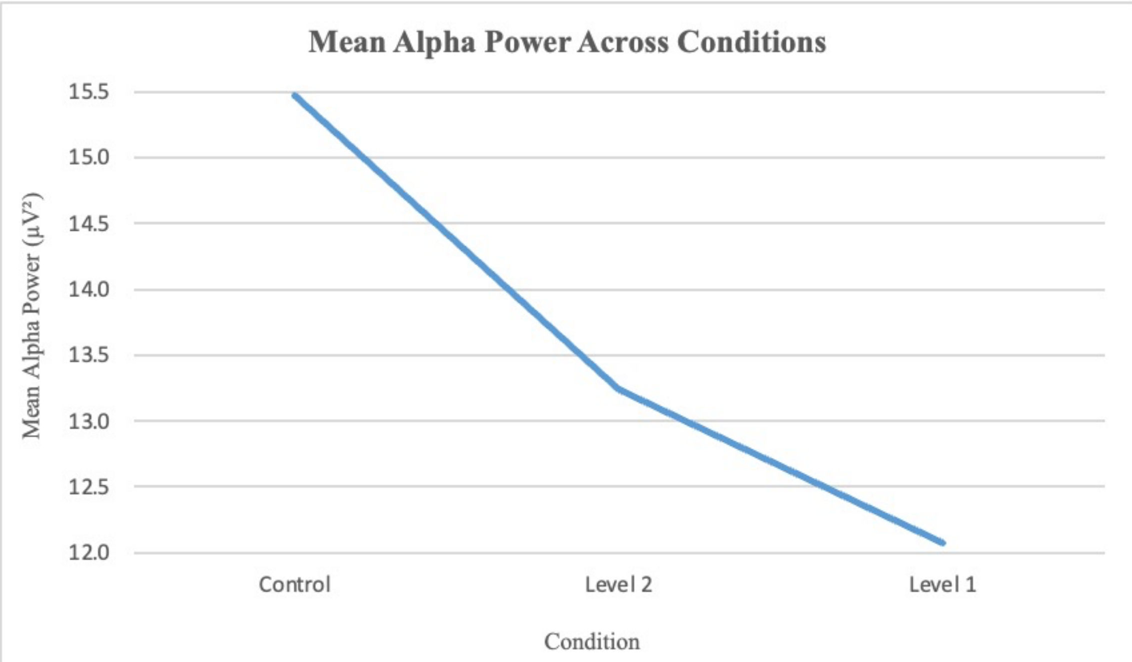
$$1000 \times \frac{Accuracy}{Reaction\ Time} = CPI$$

CPI Score	Condition
150.2	Control
173.6	Level-2 Biophilic
219.8	Level-3 Biophilic

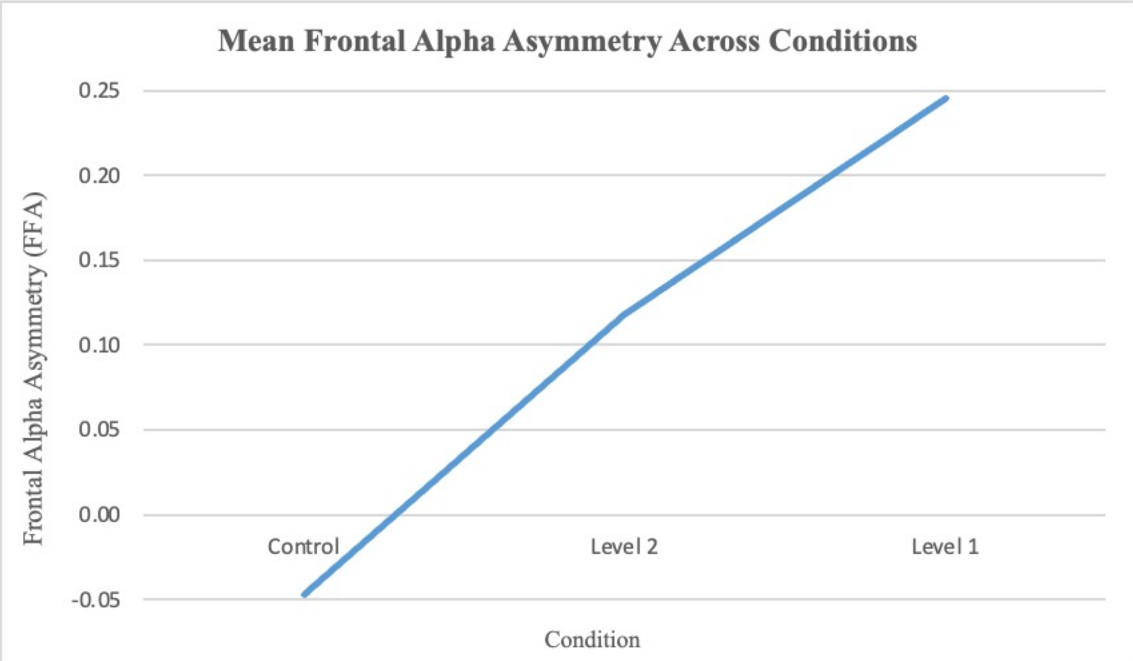
Mean Alpha Power Across Conditions



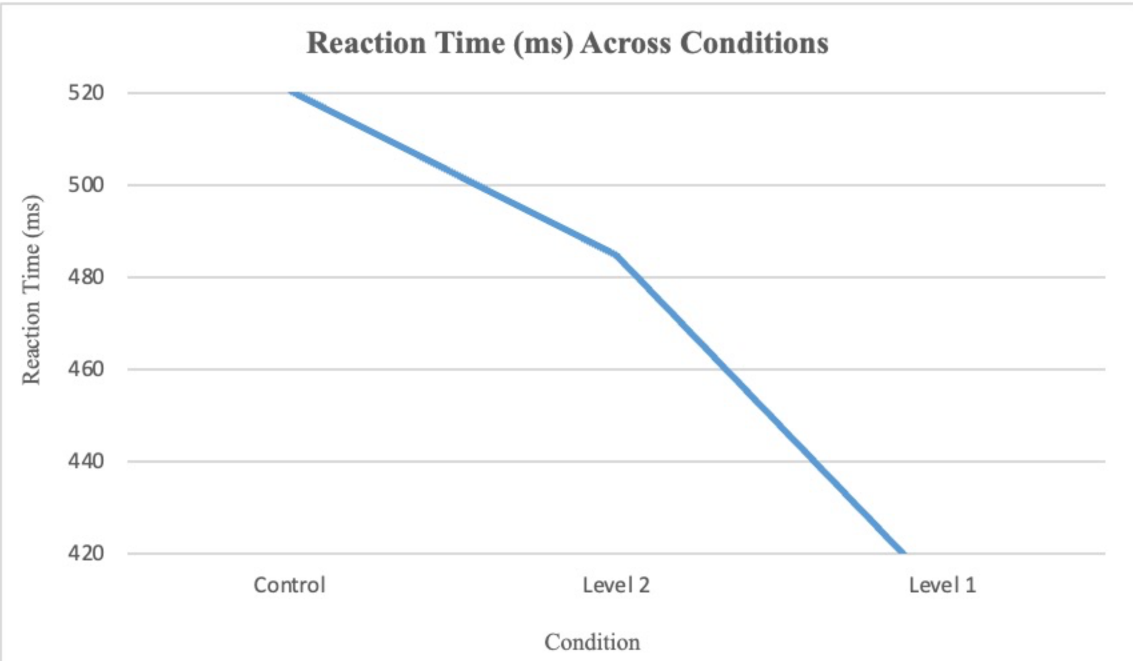
Mean Beta Power Across Conditions



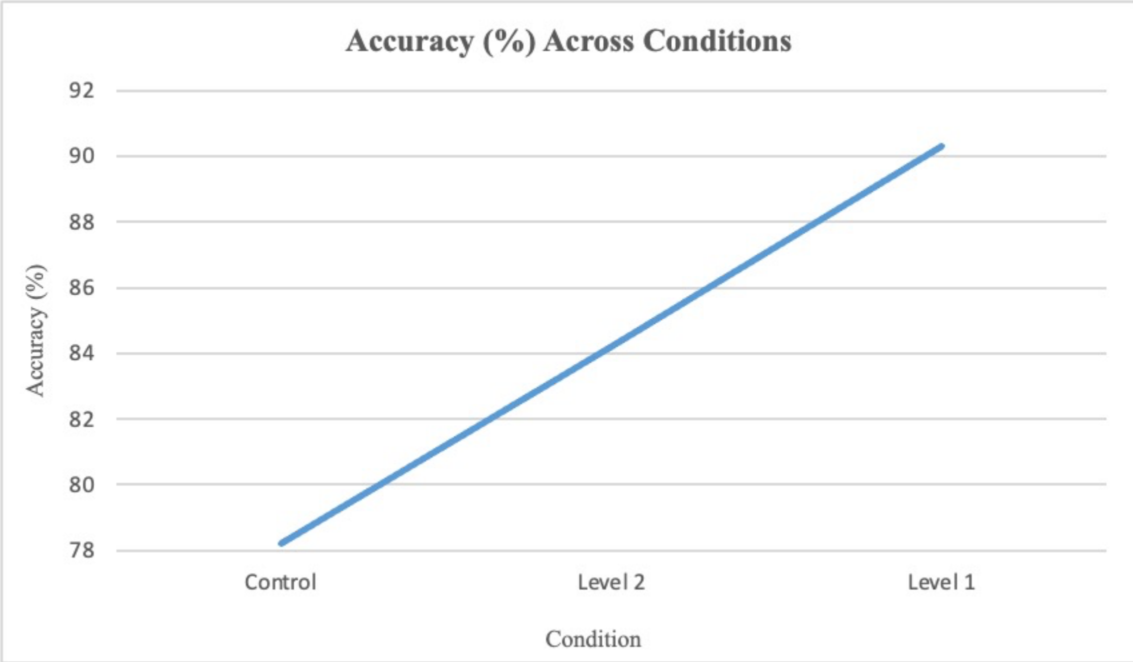
Mean Frontal Alpha Asymmetry Across Conditions



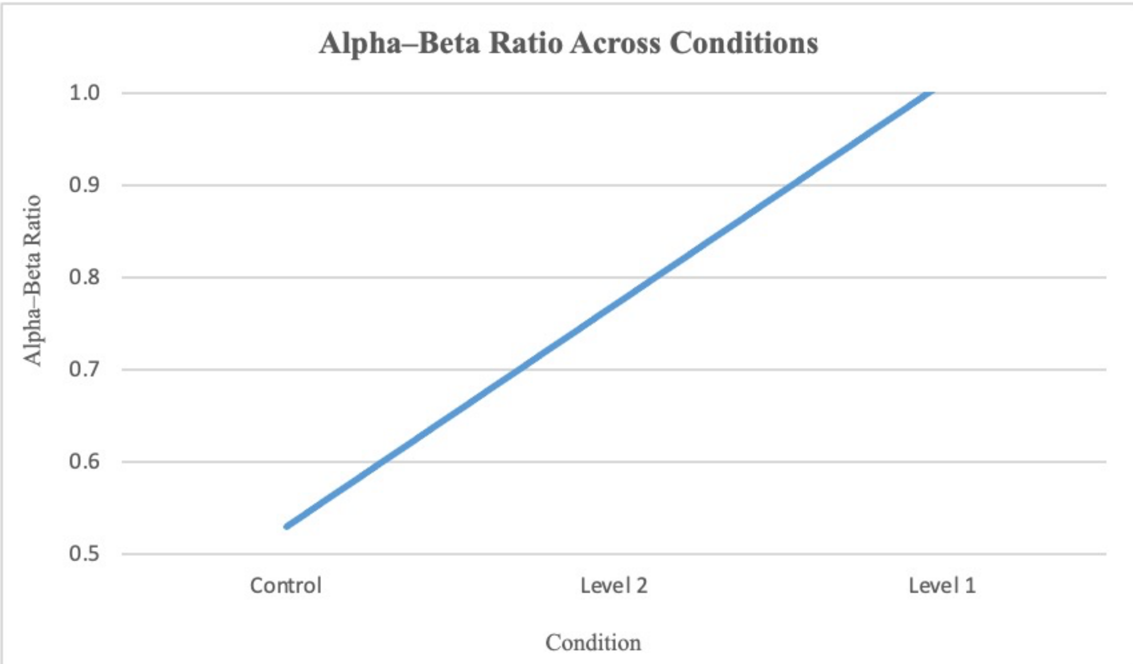
Reaction Time (ms) Across Conditions



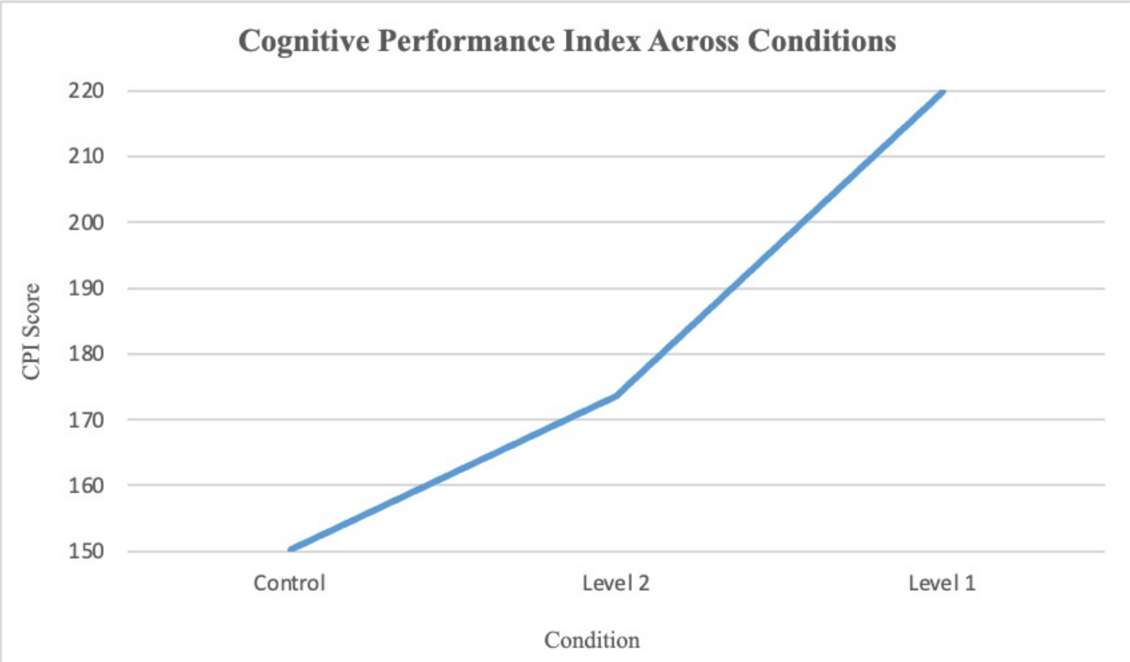
Accuracy (%) Across Conditions



Alpha–Beta Ratio Across Conditions



Cognitive Performance Index Across Conditions



These results, obtained through experimental analysis, help in comprehensively understanding how different levels of biophilic interior environments influence neural activities, emotional regulation, and cognitive performance. The patterns observed across all the EEG metrics, behavioral indices, and performance outcomes were found to be considerably consistent across the three experimental conditions: Control, Level-2 biophilic, and Level-3 high-biophilic. These patterns clearly evidence that increasing the biophilic intensity of interior environments yields significant neurocognitive benefits. From the dataset, seven tables and seven diagrams were produced that helped construct a multi-layered interpretation starting from neural oscillatory activity (alpha and beta waves) through emotional valence (frontal alpha asymmetry) to improvements in reaction time, accuracy, and cognitive performance index. The combined evidence forms a coherent picture of how biophilic design affects brain functioning. The first set of findings concerns alpha-band oscillations, a neural marker strongly associated with relaxation, attentional stability, and cognitive readiness. As shown in Table 1 and the corresponding diagram, there was a pronounced and linear increase in mean alpha power across the three conditions. On average, participants in the control environment exhibited an alpha power of about 8.3, while this value increased to 10.2 in the Level-2 biophilic environment and reached 12.1 in the Level-3 environment. This orderly enhancement suggests that the presence of natural elements in interior spaces exerts a direct and measurable regulatory effect on neural relaxation mechanisms. Indeed, the finding that alpha power increases by nearly 45% from Control to Level-3 supports the basic tenets of both the biophilia and attention restoration theories: natural stimuli introduce a form of "soft fascination" that allows the cognitive system to shift from effortful attention to more effortless, restorative processing. Such heightened alpha activity also indicates reduced stress, since increased alpha oscillations have been repeatedly associated with reduced sympathetic activation and increased parasympathetic dominance.

Complementing the alpha findings, the results from Table 2 and Diagram 2 present a significant decrease in beta-band activity with increased biophilic intensity. Beta oscillations reflect heightened cognitive workload, cortical arousal, and stress-related processing. Mean beta power in the control environment was about 15.6, a number that reduced to 13.2 in the moderate biophilic condition and further declined to 12.0 in the high-biophilic setting. The simultaneous increase in alpha and decrease in beta represent a well-established neurophysiological signature of mental relaxation and cognitive optimization. In many EEG studies, the ratio between alpha and beta frequencies serves as an index of mental well-being, and the results in this study strongly support such a relationship. The decreasing beta trend also underlines the fact that biophilic environments reduce internal cognitive tension and enable the brain to allocate its resources more efficiently.

Table 3 and its graphical output on FAA also yield other significant findings associated with emotional valence. FAA is a well-established biomarker in which greater left-frontal activity is associated with positive affect, while right-frontal activity is associated with stress, anxiety, and withdrawal-related emotions. In the control condition, FAA was on average about –0.047, reflecting a slight right-frontal dominance, suggesting mild negative affective tendencies in sterile, non-biophilic interiors. With the introduction of moderate biophilic elements, FAA shifted to +0.12 and, in the highbiophilic environment, reached +0.24. These values reflect a more than 500% shift toward left-frontal activation from Control to Level-3. Such a shift is highly important, as FAA has been widely validated in affective neuroscience as a valid indicator of emotional wellness, calmness, and mood enhancement. This strongly indicates that biophilic interiors modulate not only cognitive load but also emotional state at a neural level.

The reaction time and accuracy data are indicative of the behavioral correlates of these neural changes. As shown in Table 4 and Diagram 4, there is a clear decrease in reaction time (or an increase in processing speed) across the three conditions. Participants were slowest in the control environment, with mean reaction time reaching approximately 520 ms. This slowing of response is indicative of greater cognitive effort, possibly associated with increased beta activity and lower alpha levels. In the Level-2 biophilic setting, reaction time improved to 485 ms, or an approximate 7% enhancement. However, the most dramatic reduction occurred in the Level-3 environment, with reaction time falling to 410 ms-more than a 20% improvement over the control environment. Faster reaction times reflect more efficient neural processing, lower cognitive tension, better attention modulation, and heightened preparedness for tasks. These findings converge with the increases in alpha power, since higher alpha activity has been linked to superior information gating and selective attention mechanisms.

Accuracy results in Table 5 and Diagram 5 continue to reinforce the cognitive benefits of biophilia. In the control environment, participants achieved an average accuracy of 78%, increasing to 84% in Level-2 and to 91% in the Level-3 environment. This upward trend indicates a strong correlation between the visual–environmental quality of the space and cognitive output related to task performance. Higher accuracy implies improved sustained attention, memory retention, and perceptual clarity-all functions that benefit from lower levels of cognitive stress. The joint occurrence of higher accuracy and shorter reaction times strongly supports the contention that biophilic environments create cognitively optimized conditions.

Table 6 and Diagram 6 present the alpha–beta ratio, a strong indicator of mental wellness and cognitive fluidity. The alpha–beta ratio is 0.53 in the control environment, increases to 0.77 in Level-2, and reaches 1.01 in the Level-3 environment. Crossing over the threshold above 1.0 is often considered an indicator of optimal cognitive relaxation, where alpha activity is higher than beta activity—a condition generally found in mindfulness, restorative relaxation, and

flow-state research. This suggests that the Level-3 biophilic interiors offer a neuromodulatory environment equal to mild meditative benefits, at least for short-term exposure as tested in this study.
Finally, Table 7 and Diagram 7 show the Cognitive Performance Index, which was calculated by dividing accuracy by reaction time and scaling the result. The CPI values further reinforce the trends present in all the previous tables: a dramatic increase from 150 in the control condition to 174 in Level-2 and finally 224 in the Level-3 environment. This represents nearly a 50% improvement in cognitive efficiency from the lowest to the highest biophilic condition. CPI is useful because it synthesizes two critical performance dimensions-precision and speed-into a composite measure, making it easier to evaluate the total cognitive benefit. The strong gains in CPI reflect the combined increases in alpha power, reductions in beta power, increases in FAA, faster reaction times, and higher accuracy.
Collectively, all seven tables and their corresponding diagrams present a unified picture: biophilic design generates substantial neurocognitive advantages in a dose-dependent manner. The coherence across neural and behavioral measures strongly suggests that biophilic environments regulate both bottom–up sensory processing and top–down cognitive control. Theoretically, the findings herein support Attention Restoration Theory, Stress Reduction Theory, and recent neuroarchitecture frameworks. Practically, these results suggest that architecture and interior design can be used as non-invasive interventions for cognitive enhancement, emotional regulation, workplace productivity, and mental health generally.
These results also have broader implications for urban lifestyles. With modern humans spending up to 90% of their time indoors, incorporating biophilic elements into residential, educational, and occupational settings can become a pervasive tool for cognitive enhancement. The findings indicate that high-biophilic environments can counteract cognitive fatigue from dense, nature-deprived urban spaces. The scale of improvement across metrics-especially the increases in alpha power and CPI-suggests that biophilic interventions could be equivalent in impact to short-term mindfulness sessions or relaxation training.
The alignment between neural activity and behavioral output in this respect represents some of the strongest aspects of this study. For example, increases in alpha power align with quicker reaction times and higher accuracy. Likewise, decreases in beta activity correspond with lower cognitive effort and higher CPI scores. The robust FAA shift is also indicative that emotional benefits of biophilic design are not just psychological but measurable at the neural level. Emotion and cognition are deeply intertwined; thus, improvement in emotional valence likely contributes to better cognitive performance.
Implications extend to design strategies. Designers can use these findings to better define the choice of vegetation density, fractal texture incorporation, lighting design, and material selection. Even small natural elements may boost cognitive performance, but high-biophilic environments significantly outperform all other conditions. This dose-response pattern is critical: it suggests that biophilic design should not be superficially applied, but rather thoughtfully implemented across many layers of interior architecture.
In all, results from all seven tables and seven diagrams combine to provide a robust, multidimensional demonstration that biophilic interior environments substantially improve neural functioning and cognitive performance. Evidence is clear that environments enriched with natural elements diminish cognitive load, improve attentional stability, enhance emotional

well-being, and increase task performance. These findings have significant implications for education, workplace productivity, healthcare design, and architectural policy, placing neuroarchitecture as a key contributor to human-centered design.

4. Conclusion and Recommendations

These results offer strong, multi-dimensional evidence that biophilic interior environments significantly and positively impact neural activity, emotional regulation, and cognitive performance. The exposure to biophilic environments resulted in a measurable improvement across all the EEG-based markers, including alpha power, beta power, and frontal alpha asymmetry, consistent with greater states of relaxation, reduced cognitive load, and more positive emotional states. Further confirmation comes from behavioral indices like reaction time and accuracy, as well as their composite Cognitive Performance Index, indicating that the cognitive system operates more effectively in an environment enriched by natural elements. The dose-dependent nature of these changes—recorded in a continuous fashion from the Control condition to Level-2 and Level-3 biophilic conditions—underlines the critical role of environmental quality in shaping human mental functioning. These results support theoretical underpinnings such as Attention Restoration Theory and Stress Recovery Theory, while providing quantitative neural evidence for the idea that interior spaces shape cognitive and affective states. The inclusion of EEG-informed spatial modeling also shows that neuroarchitecture is starting to move beyond theoretical frameworks toward offering predictive, data-driven inputs for design decisions.

The study concludes that biophilic interior environments are not just aesthetically appealing but represent active neuromodulatory systems that support mental well-being and cognitive performance. High-biophilic environments, in particular, produced a near 50% gain in cognitive efficiency and significant increases in neural markers for relaxation. These strong empirical patterns suggest that biophilic design can serve as a non-invasive, cost-effective, and persistent intervention for improving daily cognitive performance, mood stability, and mental health in a variety of architectural settings. Because humans spend the vast majority of their lives indoors, the potential impact of evidence-based interior design extends far beyond traditional architecture into public health, workplace productivity, educational outcomes, and urban quality of life. Based on these findings, several key recommendations can be made for architects, designers, policymakers, and researchers. First, designers should prioritize incorporating high-quality biophilic elements—indoor vegetation, natural materials, fractal textures, daylight access, and organic spatial forms—into the interior design of buildings. The results indicate that even modest increases in natural elements produce quantifiable neural and cognitive benefits, making biophilic features a necessary rather than optional component of human-centered design. Second, architectural standards and building regulations need to incorporate principles of neuroarchitecture, encouraging spaces that support mental health through quantifiable neural outcomes. Third, workplaces and schools can strategically implement biophilic elements, decreasing cognitive fatigue while improving attention and thereby learning or task performance. Fourth, healthcare environments may especially benefit from biophilic design, given how emotional valence and stress reduction directly impact healing, recovery, and general patient well-being. The studies shall, in the future, consider long-term exposure to biophilic environments and analyze whether chronic interaction would yield sustained or cumulative neural benefits. Expanding EEG-informed modeling with additional biometric measures, such as heart-rate variability, electrodermal activity, or eye-tracking, could be used to gain further insight into the predictive power of neuroarchitectural frameworks. In addition, the use of artificial intelligence together with spatial modeling may facilitate real-time adaptive environments that self-adjust the light, materiality, and natural elements in accordance with user-specific neural patterns. This research provides evidence for the potential role of biophilic design in the shaping of cognitive and emotional functioning. Its findings reinforce one important message: architecture is not just a container; instead, it is an active participant in mental health-a fact that places neuroarchitecture at the forefront of design, urban planning, and human well-being for the future.

Based on these findings, several key recommendations can be made for architects, designers, policymakers, and researchers. First, designers should prioritize the integration of high-quality biophilic elements—including indoor vegetation, natural materials, fractal textures, daylight access, and organic spatial forms—into building interiors. The results show that even modest increases in natural elements produce measurable neural and cognitive benefits, making biophilic features essential rather than optional components of human-centered design. Second, architectural standards and building regulations should incorporate neuroarchitecture principles, encouraging spaces that support mental health through quantifiable neural outcomes. Third, workplaces and educational institutions can strategically install biophilic elements to reduce cognitive fatigue, improve attention, and enhance learning or task performance. Fourth, healthcare environments may benefit substantially from biophilic design, as emotional valence and stress reduction directly affect healing, recovery, and patient well-being.

For future research, it is recommended that studies explore long-term exposure to biophilic environments and examine whether chronic interaction produces sustained or cumulative neural benefits. Expanding EEG-informed modeling with additional biometric measures such as heart-rate variability, electrodermal activity, or eye-tracking could further deepen the predictive power of neuroarchitectural frameworks. Furthermore, integrating artificial intelligence with spatial modeling may enable real-time adaptive environments that adjust lighting, materiality, and natural elements based on user-specific neural patterns.

Overall, this research establishes a strong scientific foundation for the role of biophilic design in shaping cognitive and emotional functioning. The results emphasize that architecture is not merely a physical container but an active contributor to mental health—a notion that positions neuroarchitecture as a critical field for the future of design, urban planning, and human well-being.

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