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The Role of Neuroscience and Artificial Intelligence in Biophilic Architectural Design Based on the Principle of Symbiosis

Adityo[1]
[1] Faculty of Environmental and Symbiotic Science, Human Habitat Division, Prefectural University of Kumamoto, Kumamoto, Japan

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ABSTRACT

Biophilic architecture aims to create an environment that enhances connectivity between humans and nature to improve physical, mental, and emotional well-being. This review analyses 25 recent scientific journals on the application of neuroscience and artificial intelligence (AI) to optimise biophilic architectural design based on the principle of symbiosis. Results show that neuroscience provides valuable insights into human psychophysiological responses to various biophilic elements, while AI enables complex data processing, predictive modelling, and real-time design adaptation. The collaboration of neuroscience and AI can help produce a more effective, responsive to human needs, and sustainable biophilic environment. On the other hand, flexibility is demonstrated by the breadth of the architectural design process phases that can be reached through this collaboration. However, methodological and ethical challenges must be addressed to ensure responsible application.

Corresponding Author:

Adityo,
Faculty of Environmental and Symbiotic Science, Human Habitat Division,
Prefectural University of Kumamoto 3-1-100, Tsukide, Higashi-ku,
Kumamoto, 862-8502, Japan
Email: G2275004@pu-kumamoto.ac.jp; adityo.roem@gmail.com ,
Phone No.: +819074218944

1. INTRODUCTION

Biophilic architecture seeks to connect humans with nature in the built environment to promote holistic well-being. This concept is based on the biophilia hypothesis, which states that humans have an innate tendency to affiliate with nature [1][2]. The symbiotic relationship between humans and nature can be strengthened by integrating natural elements such as vegetation, natural lighting, ventilation, acoustics, and organic forms in architectural design [3]. Research shows that exposure to a biophilic environment can reduce stress, improve cognitive performance, improve mood, and speed recovery [4].

However, optimal biophilic design requires an in-depth understanding of the complex interactions between humans and the environment. Advances in neuroscience and AI offer new opportunities to better understand human responses to biophilic stimuli and optimise data-driven designs. Neuroscience uses technologies such as EEG, fMRI, and physiological measurements to investigate brain and body activity related to perception, cognition, and emotion in response to the environment [5]. AI, such as machine learning, natural language processing, and computer vision, can process and interpret large data sets, uncover hidden patterns, and make predictions to inform design decisions [6].

This article was prepared when intensive tracking on the internet found a single article explicitly discussing the application of neuroscience and artificial intelligence to optimise human and natural connectivity based on symbiotic principles. Most articles deal with the combination of some of these elements. Thus, holistic research that reviews these elements comprehensively is needed. (see Figure 1)

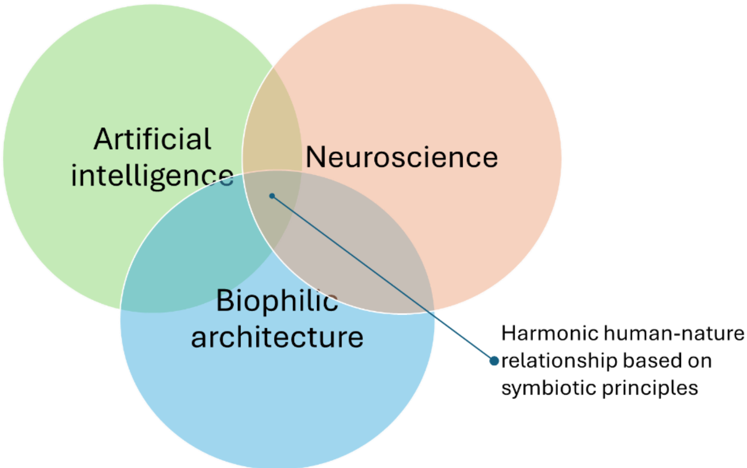

Figure 3. The intersection of artificial intelligence, neuroscience, and biophilic architecture is used to optimise the harmonisation of man and nature based on the principles of symbiosis.

This review aims to synthesise findings from the latest scientific journals on applying neuroscience and AI in biophilic architecture, focusing on improving human-natural connectivity based on the principle of symbiosis. Implications for future research and practice will be discussed, as well as ethical challenges and considerations.

2. RESEARCH METHOD

This article was prepared by researching the literature available on the internet. Literature searches were conducted on academic databases, including Google Scholar, PubMed, ScienceDirect, Web of Science, and JSTOR, with keywords: "biophilic architecture", "neuroscience", "artificial intelligence", "symbiosis", "human-natural connectivity", and variations of related terms. The inclusion criteria are: (1) Peer-reviewed scientific journals, (2) published in English between 2018-2023, (3) substantially addresses the application of neuroscience and AI in biophilic architectural design, and (4) focused on improving human-nature relations. At this stage, the author is assisted by artificial intelligence (Claude, chatGPT, and Gemini). In the next stage, the analysis is descriptive without involving artificial intelligence.

An initial search yielded 90 articles, which were narrowed down to 25 based on relevance and recency. The data extracted from each study emphasised vital findings and implications for biophilic design. Thematic analyses were conducted to identify patterns, trends, and relationships across studies. The emerging themes are categorised into (1) Neuroscience insights on response to biophilic elements, (2) Applications of AI for biophilic design optimisation, (3) Integration of neuroscience and AI for adaptive and responsive design, and (4) Methodological and ethical considerations. After the discussion, a conclusion was drawn to unify it.

3. RESULTS AND DISCUSSION

This research topic brings together three notions, namely 1) Artificial Intelligence, 2) Neuroscience, and 3) Biophilic architecture. The intersection of those three elements aims to optimise human and natural connectivity based on the principles of symbiosis. (see Figure 3.) Therefore, the following sub-chapters discuss understanding human and natural connectivity and symbiotic principles.

3.1. Notion

This sub-chapter explores the key concepts that unify the research, focusing on Artificial Intelligence, Neuroarchitecture, and Biophilic Architecture. We will discuss how AI enhances design processes, how Neuroarchitecture connects the built environment with cognitive function, and how Biophilic Architecture integrates nature to improve human well-being. The concept of human connectivity with nature and the principles of symbiosis, which emphasise the mutual relationship between humans and their environment, will also be examined. Together, these elements form the theoretical foundation that guides this research.

3.1.1. Artificial Intelligence

Artificial Intelligence (AI) is a branch of computer science that creates machines or computer programs capable of mimicking human intelligence, such as learning, understanding language, recognising patterns, solving problems, and making decisions. AI can be applied in various fields, including natural language processing, speech recognition, computer vision, robotics, and recommendation systems.

The main goal of artificial intelligence is to create systems that can operate autonomously and adaptively, increasing efficiency and effectiveness in various tasks. AI has experienced rapid development in recent decades, driven by increased computing capacity, the availability of big data, and advances in machine learning algorithms.

In general, AI can be divided into two categories:

1. Narrow AI: AI designed to perform specific tasks with limited intelligence. Examples include virtual assistants like Siri and Alexa, recommendation systems like those used by Netflix or Amazon, and programs that can beat humans in games like chess or Go.
2. General AI: AI that can understand, learn, and adapt to various tasks similarly to human intelligence. General AI is still a theoretical concept and has not yet been practised.

AI has brought many benefits, such as increased industry efficiency, medical research advances, and data analysis capabilities. However, AI development also poses ethical and social challenges, including privacy concerns, algorithm bias, and impact on the workforce.

Some key points about AI:

1. AI is designed to mimic human intelligence and perform cognitive tasks.
2. AI can learn from data and experience, adapt to new situations, and improve performance over time.
3. There are various types of AI, such as machine learning, deep learning, natural language processing, computer vision, and robotics.
4. AI is used in various fields, including healthcare, finance, transportation, manufacturing, and entertainment.
5. Examples of AI applications include virtual assistants, recommendation systems, facial recognition, autonomous vehicles, and medical diagnostic systems.
6. AI developments can potentially improve efficiency, productivity, and quality of life, but they also raise ethical concerns and social impacts that must be considered.

In summary, AI is a field of computer science that focuses on developing intelligent systems that can perform tasks that typically require human intelligence, aiming to increase efficiency and assist humans in various aspects of life.

In the world of architecture, AI has been widely utilised. Following its character, AI will continue to learn so that, over time, its vocabulary is growing. One example of using AI to search for biophilic architecture ideas is presented in Figure 4. As seen in the image, the AI seeks to describe a biophilic architecture based on information in its database. It needs to be developed further as an initial idea to make it feasible to build.

Figure 4. Dall-e's interpretation of biophilic architecture.

3.1.2. Neuroscience

Neuroscience, or neuroscience, studies the nervous system, including structure, function, development, genetics, biochemistry, physiology, pharmacology, and other brain and nervous system pathologies. Neuroscience covers a wide range of disciplines, from molecular and cellular biology to psychology and cognitive, to understand how the brain and nervous system work, how they affect behaviour and mental function, and how they are affected by illness or injury.

Some of the main topics in neuroscience include:

1. Brain Structure and Function: Understand how different parts of the brain and neurons work together to process information and control behaviour.
2. Neuroplasticity: Examines the brain's ability to change and adapt in response to experience, learning, or injury.
3. Neurotransmission: Understand how chemical and electrical signals are transmitted between neurons and how this affects brain function.
4. Neurological Diseases: Research the causes and treatment of conditions such as Alzheimer's, Parkinson's, stroke, and schizophrenia.
5. Behavior and Cognition: Study how the brain influences thoughts, emotions, and actions, including learning, memory, and decision-making.
6. Emotions and motivation: Neuroscience research also investigates the neural mechanisms underlying emotions, motivation, and reward systems in the brain.
7. Neuroscience technology: Advanced tools such as brain imaging (MRI, PET, EEG) and optogenetics study brain function and develop therapies for nervous disorders. Neuroscience is a highly interdisciplinary field, combining knowledge from biology, chemistry, physics, mathematics, computer science, and the social sciences to solve the mysteries of the nervous system and improve human health.

Currently, neuroarchitecture is developing [7][8]. Neuroarchitecture works in multi-sensory concepts. It enriches the idea of architecture in general, which is more dominantly mono-sensory, namely visual. Neuroarchitecture combines neuroscience with architecture. It is expected that buildings designed with a microarchitectural approach are more efficient in presenting comfort because they are achieved multi-sensorily [9][10].

The merging of artificial intelligence with neuroscience has the potential to be positive for developing biophilic architectures. According to the characteristics of artificial intelligence, the more references to artificial intelligence and neuroscience associated with biophilic architecture, the better the merger results. Figure 5 is the result of a text-to-image Bing designer. The interpretation of artificial intelligence in biophilic architectural design with a neuroscience approach produces relatively fresh work, although it still needs to deepen its impact on human nerves.


Figure 5. Two AI-made biophilic architectural drawings made with Bing Designer.

3.1.3. Biophilic architecture

Biophilic architecture is a design approach that aims to connect humans with nature in the built environment. This concept is based on the biophilia hypothesis, which states that humans have an innate tendency to affiliate with nature and other life forms.

Some of the critical principles of biophilic architecture include:

1. Visual connection with nature: Integrate natural elements such as plants, water, and natural landscapes into building design.
2. Non-visual connection with nature: Incorporate elements such as the sound of water, the scent of plants, and temperature variations to engage the non-visual senses.
3. Variation in space: Creating spaces with differences in height, openness, and scope to mimic natural variations.
4. Presence of water: Include water features such as ponds, waterfalls, or walls of water to provide a calming and refreshing effect.
5. Dynamic and diffused light: Use natural light and variety throughout the day to create a healthy and pleasant environment.
6. Biomorphic shapes and patterns: Using nature-inspired shapes, patterns, and textures in design elements such as furniture, walls, and floors.
7. Relationship with natural systems: Designing buildings that respond to local climatic, ecological, and landscape conditions.

The benefits of biophilic architecture include improved mental and physical health, reduced stress, increased productivity and creativity, and an increased sense of overall well-being. This approach is applied in various buildings, such as offices, hospitals, schools, and residential homes. Biophilic architecture aims to create healthier, more enjoyable, and sustainable spaces that improve residents' quality of life by connecting humans with nature in the built environment.

3.1.4. Human connectivity with nature

Human and natural connectivity refers to the deep and interrelated relationship between humans and the natural environment. This concept emphasises the importance of understanding and appreciating the interconnectedness of humans with natural ecosystems and how these relationships affect physical, mental, and spiritual well-being.

Some essential aspects of human and natural connectivity include:

1. Dependence: Humans depend on nature for basic needs such as clean air, water, food, and shelter. Natural ecosystems provide essential services that sustain human life.

2. Health and well-being: Contact with nature has been shown to benefit human physical and mental health, including reducing stress, improving mood, and strengthening the immune system.
3. Cultural and spiritual identity: Many cultures and spiritual traditions worldwide profoundly connect with nature, considering it a source of identity, wisdom, and meaning.
4. Learning and inspiration: Nature provides endless opportunities to learn, discover, and get inspired. Observing and interacting with nature can encourage creativity, innovation, and problem-solving.
5. Responsibility and stewardship: Understanding our connectivity with nature fosters a responsibility to protect and preserve the natural environment. It encourages sustainability practices and environmental stewardship.
6. Recovery and resilience: Contact with nature can aid recovery from trauma, illness, and other life challenges. A connection with nature can build resilience and adaptability.
7. A sense of belonging and community: Sharing experiences in nature can foster a sense of belonging and strengthen community ties, creating connections between individuals and crossing differences.

By embracing and maintaining our connectivity with nature, we can create healthier, resilient, sustainable societies that value and protect the natural world. It entails a shift in how we design our living spaces, interact with the environment, and foster a connection with nature in our daily lives. Figure 6 presents an AI design that incorporates natural elements (plants, water) in the interior to maintain the connectivity of residents to nature outside.

Figure 6. Image generation results in Bing Creator responding to biophilic architecture prompts, where natural elements are incorporated into the interior.

3.1.5. Principles of symbiosis

The principles of symbiosis refer to the rules or concepts underlying symbiotic interactions: close and mutually beneficial relationships between two or more organisms. These principles describe the characteristics and dynamics of symbiotic relationships. Some of the main principles of symbiosis include:

1. Mutualism: All organisms benefit from the interaction in mutualism symbiosis. Each symbiotic partner provides services or resources to benefit the other, creating mutually beneficial relationships.
2. Specificity: Symbiotic relationships are often precise, with symbiotic partners who have evolved to meet each other's needs. They may have particular adaptations that allow for effective interaction.
3. Intimacy: Symbiosis often involves close physical contact or integration between symbiotic partners. They may share living space, as in the case of microorganisms living inside their host's body.
4. Dependence: In some symbiotic relationships, symbiotic partners become highly dependent on each other for survival and reproduction. They may not be able to survive or reproduce without the presence of their symbiotic partners.

5. Coevolution: Symbiotic partners often undergo a shared evolution over time, with changes in one partner driving adaptation in the other. This process of coevolution can lead to increased specialisation and interdependence.
6. Dynamic equilibrium: A symbiotic relationship involves a dynamic balance between symbiotic partners. They actively respond and adjust to each other's changes, maintaining the relationship's stability over time.
7. Variation: Symbiosis can take many forms, including endosymbiosis (one organism living inside another), ectosymbiosis (one organism living on the surface of another), and intermediate symbiosis (close but separate living partners).

By understanding the principles of symbiosis, we can appreciate the complexity and importance of interactions between species in natural ecosystems. These concepts can also be applied in other contexts, such as human relations or systems design, to foster cooperation, interdependence, and mutual benefit.

3.2. Partial Unification of Elements

This sub-chapter examines the partial unification of key elements drawn from literature on neuroscience, AI, and biophilic design. It begins by exploring how neuroscience insights into human responses to biophilic elements can inform design practices, enhancing well-being and cognitive function. The discussion then moves to the application of AI in optimising biophilic design, where advanced tools improve the prediction and impact of these elements. The integration of neuroscience and AI for adaptive and responsive design is also highlighted, emphasising how this combination can lead to innovative architectural solutions that dynamically respond to user needs. Finally, the sub-chapter addresses the methodological and ethical considerations of merging these fields, acknowledging such interdisciplinary approaches' potential and challenges.

3.2.1. Neuroscience insights into responses to biophilic elements

Some studies reviewed the neuroscience basis of human responses to biophilic design elements. Abdullah et al. used EEG to show that brief exposure to virtual nature videos reduced stress-related brain activity and increased relaxation compared to urban videos [11]. Funahashi, albeit indirectly, found that cognitive tasks performed in rooms with plants and natural lighting resulted in greater activation in the dorsolateral prefrontal cortex and improved executive function [12]. Some studies have found that subjects reported more positive moods and lower arousal after sitting in a biophilic rooftop garden for 15 minutes [13][14].

Other studies focus on specific design parameters. Li et al. used eye-tracking to show that curved and fractal contours on building facades attract more visual fixation than linear design and show an innate preference for organic shapes [15]. Zhang found that exposure to dynamic light that mimics natural circadian rhythms improved alertness and task performance compared to static lighting. These findings provide neuroscience evidence for the benefits of biophilic design elements and may guide feature selection for optimal effect [16].

Neuroscience can provide valuable insights to aid biophilic architecture by informing designs that improve human cognitive, emotional, and physiological well-being. Here are some ways neuroscience can contribute to biophilic architecture:

1. Understanding the brain's response to nature: Neuroscience can investigate how the human brain responds to natural elements such as plants, water, and natural light. Research can uncover the neural mechanisms underlying the therapeutic and calming effects of exposure to nature, providing scientific evidence for the benefits of biophilic design.
2. Optimizing sensory stimuli: Neuroscience can help identify the types of sensory stimuli (visual, auditory, olfactory, etc.) most effective in evoking positive and therapeutic responses in the brain. These findings can inform the selection and placement of biophilic elements, such as colour, texture, sound, and scent, to maximise their impact on well-being.
3. Design for cognition and performance: Neuroscience research can uncover how the built environment affects cognitive functions such as attention, memory, and problem-solving. These insights can be applied in biophilic architectures to create spaces that enhance mental performance and support learning and productivity.

4. Managing stress and emotions: Neuroscience can investigate neural circuits involved in stress response and emotion regulation, providing insight into how biophilic design can help reduce stress and improve emotional well-being. For example, research can inform the placement of green spaces or water features to maximise their calming effect.
5. Circadian rhythms and sleep: Neuroscience can inform how biophilic architecture can support natural circadian rhythms and improve sleep quality through natural light, temperature control, and other design elements. Optimising the built environment for circadian health can significantly benefit overall well-being and performance.
6. Neuroplasticity and recovery: Neuroscience research on neuroplasticity, or the brain's ability to change and adapt, can inform how biophilic architecture can support recovery from injury, disease, or neurological conditions. Designing an environment encouraging nerve growth and reorganisation can aid rehabilitation and healing.
7. Individual preferences and behaviours: Neuroscience can investigate individual differences in response to the biophilic environment based on personality, cultural background, and previous experiences. Understanding individual choices and behaviours can inform personalised and inclusive biophilic design.

By integrating findings from neuroscience into the design process, biophilic architecture can create an environment scientifically optimised for human well-being. A multidisciplinary approach that combines neuroscience, environmental psychology, and architecture can result in more effective spaces that foster a deeper connection between humans and nature in the built environment.

3.2.2. Application of AI for biophilic design optimisation

Some of the studies reviewed explored the use of AI to optimise biophilic design. Gradisar et al. developed a generative algorithm that generates a spatial layout by considering several biophilic parameters, including access to nature, lighting, and shortcuts [17]. This algorithm results in designs with higher biophilic performance than the manual approach. Yang et al. trained deep learning models on an extensive database of room images to predict visual comfort levels based on features such as the number of plants, type of lighting, and colour palette. This model can be used to evaluate and optimise biophilic design [18].

Another AI approach involves multi-objective optimisation. Afroz et al. developed a framework to optimise façade design, considering natural lighting performance, energy efficiency, and biophilic aesthetics [19]. They devised a façade design using evolutionary algorithms that balances some of these goals. These studies demonstrate the potential for AI to automate and optimise certain aspects of biophilic design and enable a more comprehensive exploration of design spaces and more optimal solutions.

Artificial intelligence (AI) can play an essential role in assisting biophilic architectures in a variety of ways:

1. Generative design: AI can generate and optimise biophilic designs by considering parameters such as solar orientation, airflow, integration of natural elements, and user preferences. AI algorithms can explore multiple design options and propose solutions optimising performance and biophilic aesthetics.
2. Simulation and modelling: AI can perform biophilic environment simulation and modelling to predict performance, thermal comfort, air quality, and other aspects. It helps architects make the right design decisions and optimise the integration of natural elements into the building.
3. Data analysis: AI can analyse big data from sensors, user surveys, and other sources to gain insights into user preferences and behaviour in a biophilic environment. This information can be used to inform design decisions and improve the effectiveness of biophilic interventions.
4. Real-time adaptation: The AI system can monitor and adjust the building environment based on environmental conditions and user preferences. For example, the system can adjust lighting, temperature, and humidity to optimise user comfort and well-being while maximising biophilic benefits.
5. Predictive maintenance: AI can monitor and predict the maintenance needs of biophilic elements such as plants, hydroponic systems, and water features. AI can identify potential problems and recommend proactive maintenance actions by analysing data from sensors and monitoring systems.
6. Evaluation and feedback: AI can help in the performance evaluation of biophilic designs by analysing post-occupancy data and user feedback. These insights can refine future designs and inform best practices in biophilic architecture.

7. Personalization: AI can personalise biophilic environments based on individual preferences and needs. By learning from user behaviour and feedback, AI systems can adjust lighting, temperature, and other biophilic element settings to create an optimal environment for each user.

By leveraging AI's data analysis, optimisation, and decision-making capabilities, biophilic architectures can become more responsive, adaptive, and effective in creating healthy, enjoyable environments that connect humans with nature. Collaboration between architects and AI experts can result in innovative solutions that advance the goals of biophilic architecture and improve occupant well-being.

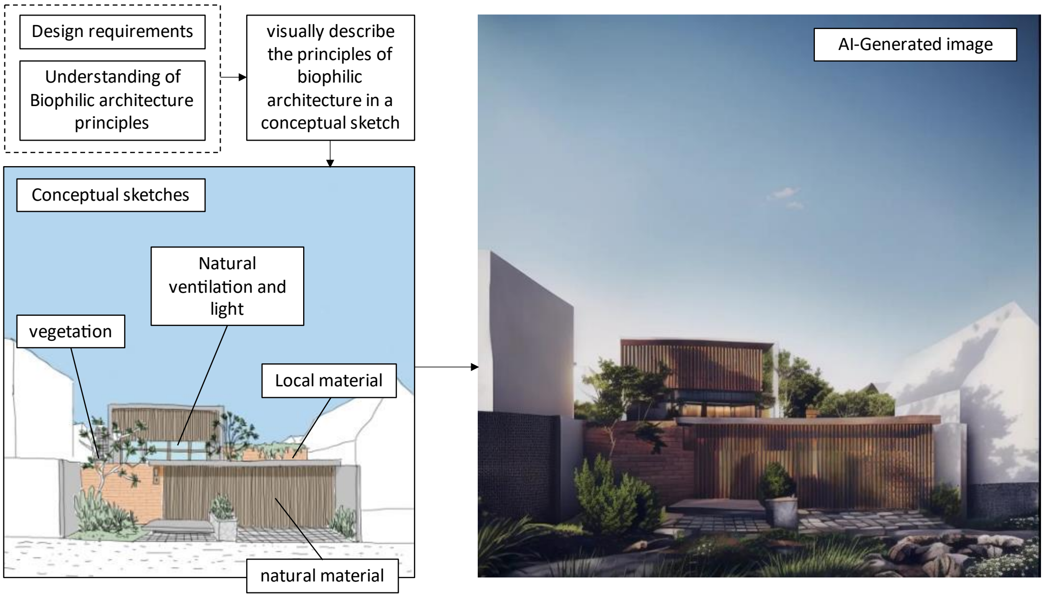

Figure 7. The use of AI to support the architectural conceptual design phase – 1.

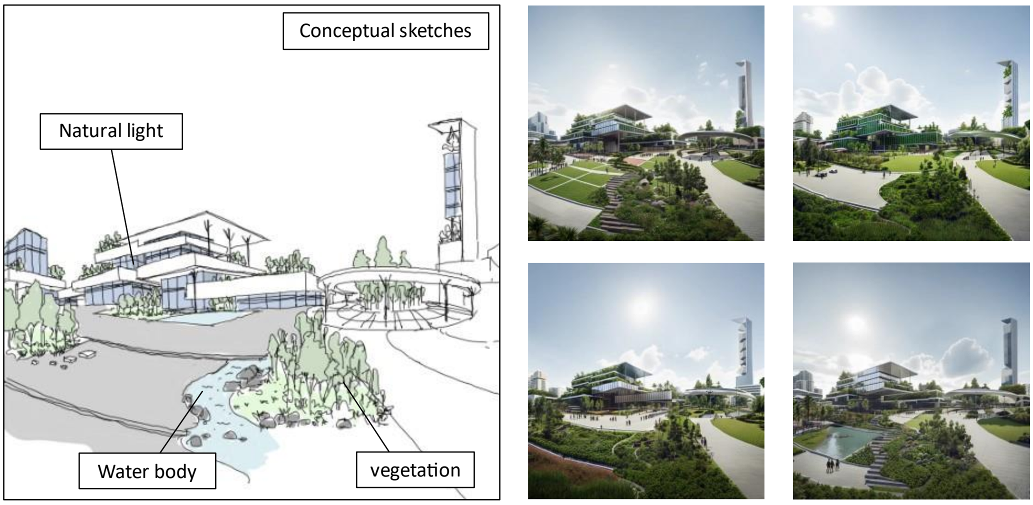

Figure 6. The use of AI to support the architectural conceptual design phase - 2.

On the other hand, with the architect's background knowledge of biophilic architecture, AI can also help the design process efficiently, from the conceptual design process to design development. Figures 5 and 6 show the process of searching for ideas through design sketches by visually translating biophilic design principles, which AI then generates for a villa design (figure 5) and a university building design proposal (figure 6). design requirement control by the architect through sketches and design development capabilities by AI can help the design process run efficiently.

3.2.3. Integration of neuroscience and AI for adaptive and responsive design

Several recent studies explored the integration of neuroscience and AI to create adaptive and responsive biophilic environments. Sheikh et al. propose a system that uses real-time physiological sensing (e.g., heart rate, skin response) and learning algorithms to adapt environmental parameters, such as lighting and temperature, to individual affective states [20]. Mollazadeh et al. demonstrated a responsive installation that uses computer vision to detect the number and behaviour of occupants and adjust the display of digital natural elements to optimise the biophilic experience [21].

This approach can be extended to more extensive settings. For example, Tarek et al. envision smart biophilic cities that use advanced technologies (such as neuroscience and AI) to tailor green infrastructure, transportation, and services based on residents' needs in real-time [22]. While these visions are still speculative, they demonstrate the potential of integrating neuroscience and AI to create highly responsive environments that optimise human well-being and ecological sustainability.

Integrating neuroscience and artificial intelligence (AI) can significantly advance the development of biophilic architectures by creating a more data-driven, responsive, and personalised approach to design centred on human well-being. Here are some ways this integration can help:

1. Data-driven design: Neuroscience can provide empirical data on human physiological and psychological responses to various biophilic elements, while AI can analyse and interpret this data to gain actionable insights. Combining neuroscience data into AI algorithms makes it possible to make evidence-based design recommendations that optimise the well-being benefits of biophilic features.
2. Simulation and testing: AI can create models and simulations of biophilic environments that incorporate neuroscience principles by simulating human responses to various design configurations, testing and refining designs before construction is possible, saving time and resources while ensuring optimal results for user well-being.
3. Real-time monitoring and adaptation: Combining real-time neuroscience data collected through sensors and wearables (such as EEG or heart rate trackers) with AI algorithms makes it possible to create an adaptive biophilic environment that responds to users' physiological and emotional states in real time. Based on neuroscience data, AI can adjust lighting, temperature, sound, and other elements to optimise user comfort and well-being.
4. Personalization: Individuals may respond differently to biophilic elements based on genetics, life experiences, and health conditions. By analysing personal neuroscience data using AI, it is possible to make personalised biophilic design recommendations tailored to each user's unique needs and preferences, thereby maximising benefits for their well-being.
5. Machine learning and continuous improvement: Machine learning algorithms can continuously learn and improve biophilic design recommendations by incorporating new neuroscience data from various users and environments. This approach can lead to a more refined and sophisticated understanding of human interaction with biophilic elements, enabling continuous refinement and design optimisation.
6. Integration with other technologies: AI can act as a bridge between neuroscience and other technologies relevant to biophilic architecture, such as climate control systems, lighting, and acoustics. Integrating neuroscience insights into these systems using AI makes it possible to create a more responsive and cohesive environment that holistically supports user well-being.
7. Evaluation and feedback: AI can assist in continuously evaluating biophilic designs by analysing neuroscience data collected from users over time. These insights can be used to identify areas for improvement, track the effectiveness of design interventions, and inform future iterations and refinements of the design.

By harnessing the combined power of neuroscience and AI, biophilic architecture can become more evidence-based, responsive, and personalised, fostering the development of more effective environments that optimise human well-being while strengthening our connection to nature in the built space.

Neuroscience and artificial intelligence (AI) approaches can be essential in creating biophilic architectures that optimise symbiosis between humans and nature. By integrating insights from neuroscience and AI analytic capabilities, designing environments that effectively foster mutually beneficial and adaptive relationships between human inhabitants and natural elements is possible. Here are some specific ways this combined approach can be applied:

1. Evidence-based design: Neuroscience can provide empirical evidence on human physiological and psychological responses to various biophilic features, such as plants, water, natural light, and biomorphic patterns. AI can analyse this data to identify design elements that most effectively foster a sense of connectivity with nature and improve human well-being. It can inform evidence-based design guidance for biophilic architectures optimising health and wellness outcomes.
2. Modelling and simulating symbiotic relationships: AI can create complex models and simulations of symbiotic interactions between human occupants and biophilic elements in the built environment. By incorporating neuroscience data on human responses and the dynamics of natural ecosystems, the model can help architects understand and optimise the flow of energy, matter, and information between human and natural systems, driving mutually beneficial and sustainable outcomes.
3. Real-time monitoring and adaptation: By combining real-time neuroscience sensors (such as EEG or heart rate trackers) with AI algorithms, it is possible to create an adaptive biophilic environment that responds to residents' physiological and emotional states in real time. AI can adjust lighting, temperature, ventilation, and other elements to optimise human comfort while also considering the needs of biotic elements, creating a dynamic symbiosis between residents and their environment.
4. Symbiotic principles, such as mutualism and coevolution, can inspire regenerative design approaches to biophilic architecture. AI can help identify and optimise opportunities for regenerative design, such as integrating food production or wastewater treatment systems into the built environment to reinforce human and natural systems mutually. Neuroscience data can help guide these designs to ensure they are conducive to human well-being.
5. Continuous evaluation and improvement: AI can be used to monitor and evaluate the performance of biophilic architectures over time by incorporating neuroscience data on occupant responses and preferences as well as environmental sustainability metrics. This analysis can identify opportunities for iterative improvement and allow the environment to evolve adaptively to optimise the symbiosis between human inhabitants and natural elements.
6. Personalization: Individuals may respond differently to biophilic features based on cultural background, life experiences, and sensory sensitivity. By analysing personal neuroscience data using AI, it is possible to create personalised biophilic design recommendations tailored to optimise well-being and connectivity with nature for each occupant, thereby fostering deeper symbiotic relationships at the individual level.
7. Integrated system design: Biophilic architecture optimising symbiosis requires integrating various structural, environmental, and biotic elements. AI can help manage this complexity by optimising design for multiple purposes, identifying synergies between systems and components, and enabling an integrated approach that treats buildings as complex ecosystems of interrelated human, natural, and technological elements.

By combining neuroscience and AI intelligence in this way, biophilic architecture can become a transformative field that advances symbiosis between humans and nature in the built environment. This approach has the potential to create spaces that are not only ecologically sustainable and regenerative but also proactively foster health, well-being, and connectivity to nature for those who live in them. By optimising outcomes for human and non-human natural systems, biophilic architectures driven by neuroscience and AI can be powerful catalysts for healing our connection to the natural world and reimagining our role on the broader web of life (see Figure 7).

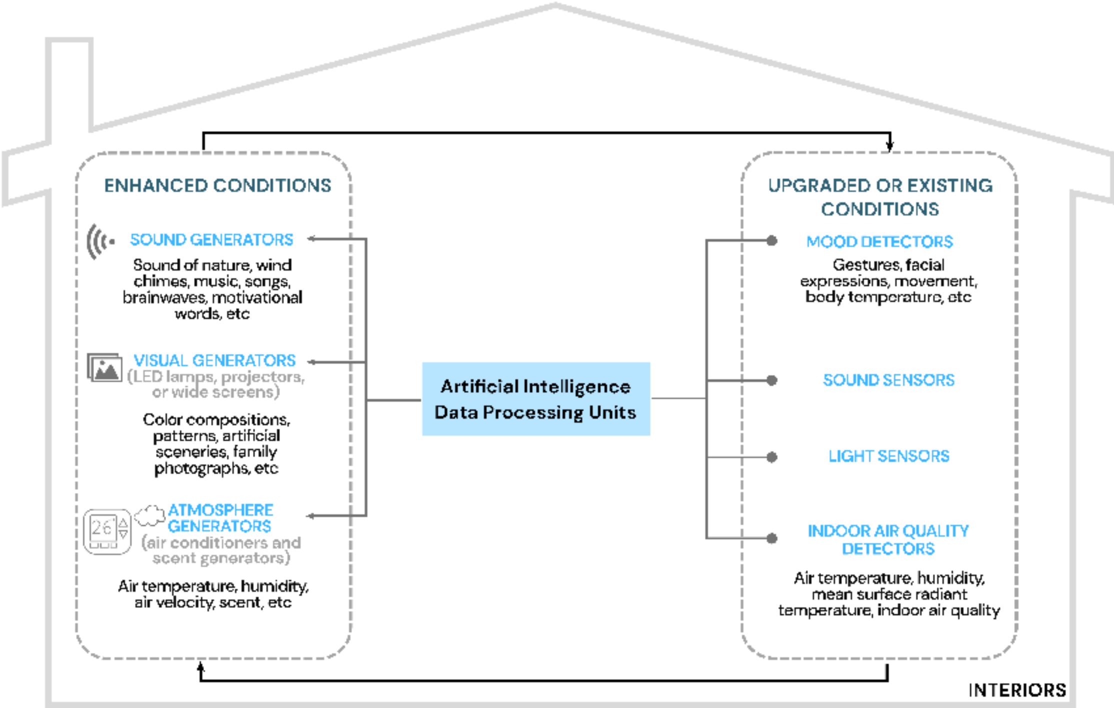

Figure 7. The use of AI to create environmentally responsive interiors for sustainable occupant comfort [23].

3.2.4. Methodological and ethical considerations

While showing positive promise, applying neuroscience and AI in biophilic design poses methodological and ethical challenges. Wang et al. discuss difficulties in designing ecologically valid architectural neuroscience studies while controlling for confounding variables [24]. They emphasise the importance of standard protocols and reference data sets. Wang also warned of potential bias in AI models that could amplify inequalities if not critically examined. They suggest strategies for equitable and inclusive AI in architectural design.

Concerning physiological and behavioural data collection, privacy and consent concerns were also raised [25]. Clear ethical guidelines are needed to ensure responsible use of data and protect individual autonomy. In addition, some researchers question the implications of overly prescriptive AI-driven design, which could potentially reduce human creativity and cultural adaptation [26]. Balancing optimisation with flexibility and openness in the design approach will be necessary.

3.3. The Role of Neuroscience and Artificial Intelligence in Biophilic Architecture Design Based on the Principle of Symbiosis

A common thread can be drawn from the above discussion. Biophilic architecture is a design approach that aims to create a space and built environment harmonious with nature by integrating natural elements into architectural design. This concept is based on the understanding that humans have a strong attachment to nature and that exposure to nature can benefit human physical and mental health.

In its development, biophilic architecture increasingly utilises the principles of symbiosis, namely mutually beneficial reciprocal relationships between humans, buildings, and the natural environment. Biophilic architecture seeks to create a sustainable and adaptive ecosystem through symbiosis.

It is where neuroscience and artificial intelligence can play an important role. Neuroscience, the science that studies the nervous system and brain, can provide deep insights into how the built environment affects human cognitive and emotional well-being. By understanding the mechanisms of human perception, emotion, and behaviour, architects can design spaces more responsive to users' psychological needs.

Meanwhile, artificial intelligence enables complex data processing and modelling of various design scenarios. Machine learning algorithms can analyse user preferences, behaviour patterns, and physiological responses to various biophilic design features. Thus, AI can assist architects in optimising building performance, energy efficiency, and environmental quality in real time.

Integrating neuroscience and AI in symbiosis-based biophilic architectures can result in more adaptive, responsive, and regenerative designs. For example, intelligent building systems with sensors and actuators can adjust lighting, temperature, and air quality conditions according to circadian rhythms and user preferences. Kinetic facades and responsive landscapes can adapt to seasonal and climate changes to maximise thermal comfort and energy conservation.

Artificial intelligence can aid in planning and managing symbiotic urban ecosystems on a larger scale. By analysing environmental, demographic, and behavioural data, AI can optimise green space layout, ecological connectivity, and green infrastructure to improve city resilience and quality of life for citizens.

Applying neuroscience and AI in biophilic architecture requires further research and experimentation. The challenge is integrating neuroscience insights and AI capabilities with human creativity and sensitivity in the design process. However, with synergistic collaboration between architects, neuroscientists, and AI experts, the potential of symbiosis-based biophilic architecture can be further realised in a future where the built environment and nature can coexist harmoniously and sustain each other.

4. CONCLUSION

This literature review highlights the great potential of neuroscience and AI in optimising biophilic architectural design to improve human connectivity with nature based on the principle of symbiosis. Neuroscience findings provide empirical evidence on the psychophysiological benefits of various biophilic design elements, guiding feature selection for targeted effects. Meanwhile, AI techniques such as generative algorithms, deep learning, and multi-objective optimisation enable efficient exploration of vast design spaces, identifying optimal design solutions, and predictive modelling.

Further integration of these areas promises the possibility of creating a highly adaptive and responsive built environment that adapts to human circumstances and preferences in real time, thereby improving well-being and sustainability. However, these advances must also be accompanied by careful consideration of ecological validity, fairness, privacy, and ethics in data collection and application. Further interdisciplinary research is needed to refine methodologies, develop best practice guidelines, and advance visions of an intelligent, human-centred biophilic environment.

With a careful and responsible approach, neuroscience and AI have the potential to transform the way we design and interact with the built environment, fostering a more harmonious and symbiotic relationship between humans, nature, and technology. Biophilic architecture underpinned by neuroscience insights and AI capabilities can create habitats that promote holistic well-being while proactively adapting to changing environmental and human needs. Integrating these principles into education, research, and design practice will be critical to realising this potential and building a more natural, adaptive, and human-centred future.

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BIOGRAPHIES OF AUTHORS

Adityo	Adityo is a doctoral student at the Faculty of Environmental and Symbiotic Science, Human Habitat Division, Prefectural University of Kumamoto. His research focuses on landscape and rural planning. He is also involved in research projects and practical work. As an architectural practitioner, His interests are in biophilic architecture.