

## VR-Based Neurophysiological Measurement Analysis and AI-Supported Design Integration in Biophilic Hospital Interiors: Neuroarchitectural Method Proposal

Elif Sözer<sup>1</sup>, Ezgi Yılmaz<sup>2</sup>

### Abstract

Future healthcare structures will be intelligent spaces that adapt not only to aesthetic, technical, and functional aspects but also to measurable responses from the human brain and body, thereby contributing to recovery processes. The aim of this study is to establish a methodological basis for an evidence-based optimisation approach and design guide using artificial intelligence technology. This involves evaluating user responses through simultaneous neurophysiological measurements while experiencing the interior components of hospital rooms designed with biophilic parameters within a neuroarchitectural framework in a VR environment. To achieve this goal, inpatient rooms were scenario-based in a virtual environment with different biophilic elements, and the neurophysiological methods/techniques used during the user's VR experience were comparatively analysed within the framework of predefined accessibility, VR compatibility, data sensitivity, ethical compliance, and cost criteria. Subsequently, the framework for an artificial intelligence-based evaluation/recommendation approach was defined by considering the selected measurement set and biophilic design parameters together. The findings indicate that the most functional set of measurements in terms of applicability, portability, and data meaningfulness, capable of reliably capturing stress/mood/cognitive load indicators while working synchronously with VR, is Electroencephalography (EEG), Heart Rate Variability (HRV), and Galvanic Skin Response (GSR). These results demonstrate that biophilic design decisions can be optimised using artificial intelligence technology based on measurable neurophysiological responses. This study is unique in that it proposes a holistic approach to biophilic hospital rooms through VR-based neurophysiological data collection and AI-supported design optimisation, and provides a systematic framework that can transform this approach into an evidence-based design guide, thereby making significant contributions to both the literature and practice.

**Keywords:** *Neuroarchitecture, Biophilic Design, VR, AI, Neurophysiological Measurements.*

### Introduction

The rooms in inpatient wards are critical recovery environments where patients often experience stress, pain and uncertainty, and spend long periods of time. The literature strongly indicates that spatial and environmental elements in healthcare facilities, such as access to nature, daylight, views, and the use of natural colours and materials, play a decisive role in reducing stress levels, shortening the recovery process, and increasing patient satisfaction (Sozer, b, c, 2023; Ulrich, 1984; Dijkstra et al., 2006; Valentine, 2024). Ulrich's classic study, which showed that patients with a view of trees from their window were discharged sooner and used less analgesics than those with a view of a wall, is considered one of the starting points for discussions on 'healing environments' and nature-based design (Ulrich, 1984).

The biophilic design approach aims to systematise this discussion by integrating natural light, vegetation, natural materials, views, water features, and formal and textural elements inspired by nature into the built environment within a holistic framework (Ryan et al., 2014; Gillis and Gatersleben, 2015). Recent systematic studies have shown that biophilic design in hospitals can shorten hospital stays,

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<sup>1</sup> Istanbul Aydin University, Faculty of Architecture, Istanbul, Türkiye, ORCID ID: <https://orcid.org/0000-0003-4038-5569>, Email: [elifsozer@aydin.edu.tr](mailto:elifsozer@aydin.edu.tr) Telephone: +905331201692.

<sup>2</sup> Istanbul Aydin University, Faculty of Architecture, Istanbul, Türkiye, ORCID ID: <https://orcid.org/0000-0002-7230-6661>, Email: [ezgiyilmaz@aydin.edu.tr](mailto:ezgiyilmaz@aydin.edu.tr), Telephone: +905326061246

reduce stress levels, alleviate pain and anxiety, and contribute to an improved quality of experience (Al Khatib et al., 2024; Miola et al., 2025; Bulaj et al., 2025).

Maggie's Cancer Caring Centres, which hold an important place in the literature on the subject and were designed with the concept of "Architecture of Hope" to give hope to cancer patients, are one example of a "healing environment" that highlights the role of architecture in the healing process (Sozer, 2022). Studies conducted at these centres have revealed that the indoor-outdoor spatial design, the 'home-like atmosphere that fosters a sense of belonging and security' offering a multi-sensory experience in terms of visual, auditory, olfactory, and tactile connections with nature, as well as the balance between privacy and social interaction, meaningfully support the psychosocial well-being of cancer patients; These studies have revealed that the spatial experience is itself part of the healing process (Sozer, c.2023; Heathcote, 2006; Jencks and Heathcote, 2010; Tekin, Corcoran, and Urbano Gutiérrez, 2023; van der Linden, 2016). With the spread of these findings, professional organisations such as the British Medical Association have published reports and statements emphasising that building design in hospitals and healthcare facilities should be considered not merely as a functional shell but as a health input that directly affects patient recovery; they have called for priority to be given to architectural design quality in new healthcare projects (British Medical Association, 2011; British Medical Association, 2024; see also Construction Management, 2011).

The field of neuroarchitecture discipline, which emerged in parallel with these developments, examines how the characteristics of spatial phenomena such as colour, light, texture, form, sound, smell, and material are processed in the brain and their effects on cognition, emotion, and behaviour (Sozer, 2020; Karakas and Yildiz, 2020; Higuera-Trujillo et al., 2021; Abbas et al., 2024). Specifically, through the responses of regions such as the anterior cingulate cortex (ACC), parahippocampal place area (PPA), and mirror neuron networks to architectural stimuli, it has been revealed how spatial experience is intertwined with processes of affect, attention, and orientation (Abbas et al., 2024; Chatterjee et al., 2021). Although studies exist in the literature emphasising that the biophilic effect is not limited to "real nature" and that VR-based nature simulations can also be effective in reducing stress and enhancing perceived environmental quality (You et al., 2023; Kumpulainen et al., 2024), However, particularly in the neuroarchitecture literature, hospital interiors, biophilic design parameters, and neurophysiological measurements such as EEG, fMRI, HRV, GSR, and PET are rarely addressed together within the same experimental framework (Sozer, 2020; Rad et al., 2023; Bulaj et al., 2025).

Within this theoretical framework, Sozer's neuroarchitecture trilogy—Neuroarchitecture Perception Games, Neuroarchitecture Brain Conversations, and Neuroarchitecture Metamorphosis—establishes a conceptual bridge between spatial configuration, multisensory perception, and neurocognitive processes, evaluating interior design as a trigger that manipulates cognitive, emotional, and behavioural expressions by addressing it within the brain-body -space dialectic—as a trigger that manipulates cognitive, emotional, and behavioural expressions. Neuroarchitecture, a field that approaches architecture and neuroscience with a multidisciplinary understanding, measures the brain's responses to architectural structures and optimises architectural design accordingly. VR-based experimental space models, neurophysiological measurements, and artificial intelligence-supported design decision parameters provide a robust framework for evidence-based conceptual, systematic, and applicable design method proposals (Sozer, a,b,c., 2023).

Sozer, in her 2023 book *Neuroarchitecture Metamorphosis -Healing Spaces*, she proposes a neuroarchitectural design method whereby a space modelled in computer programs such as 3D Max, Lumion, and SketchUp is converted into a full-scale three-dimensional model using virtual reality (VR) applications. Users can then navigate within this simulation, and their responses to spatial phenomena are measured using neurophysiological measurements such as EEG, HRV, fMRI, GSR, PET, and eye tracking to determine their responses to spatial phenomena. She emphasises that the design can be optimised based on stimuli that elicit positive responses from the individual, thereby establishing the conceptual framework of neuroarchitecture.

Within this scope, distributed artificial intelligence, i.e. multi-agent systems, can be used in the process of optimising the space. An autonomous agent is a system placed in a real or virtual environment that collects perceptions from this environment, transforms these perceptions into situational awareness, and acts in the environment by making its own decisions in line with its objectives. The term 'autonomy' here refers to decisions being made through the agent's own internal processes rather than through external commands. Intelligent autonomous agents can act according to behavioural models in their decision-making processes: reactive (responding to immediate stimuli), inferential (analysing the situation, reasoning), or interactive (establishing mutual relationships with

other agents or the environment). In short, an agent can be defined as a ‘decision-making entity’ that perceives information from its environment, evaluates the situation based on this information, plans its behaviour, and influences the environment through its chosen actions. The same logic applies to groups: each group can be modelled through an agent that represents the highest-level decisions within that group's hierarchy.

Thus, instead of individual entities, the group's behaviour pattern is simulated as a “high-level decision-maker” factor. Each agent is autonomous, perceives the environment, responds to the environment, enables human movements to be transferred to the computer environment, and processes different techniques of artificial intelligence. Autonomous agent systems, in other words, agent-based modelling developed within the scope of artificial intelligence (Agent-based model, ABM), can recreate the appearance of complex events and predict them by simulating the simultaneous operations and interactions of multiple agents, thereby recreating the space and charting a roadmap in optimisation processes (Sozer, 2023).

Although in recent years some studies have examined the virtual nature-biophilia effect by combining VR hospital rooms, methods such as neurophysiological measurements, and machine learning (Jung et al., 2023), biophilic hospital interior parameters, brain activity and affect -mood indicators, stress biomarkers such as heart rate variability, and AI-based design optimisation components into a single, reproducible design decision system (Kumpulainen et al., 2024; Velana et al., 2022). The aim of this study is to respond to this gap by identifying neurophysiological techniques that can be used simultaneously during users' VR-based spatial experiences to evaluate hospital rooms in health structures designed with biophilic elements according to defined criteria, and to propose a neuroarchitecture-based framework for AI-supported design integration.

## **Methodology**

The “biometric approach” to be used in VR-based neurophysiological applications for hospital wards in this study refers to the simultaneous and holistic use of EEG, HRV and GSR (with eye tracking when necessary), and represents the integration of multiple neurophysiological and physiological sensors rather than a separate technique. When determining measurement methods, not only theoretical suitability but also practical applicability and compatibility with the clinical-research infrastructure were considered. Rad and colleagues' (2023) systematic review of neuroarchitectural experimental studies emphasises the balance between “field applicability”, “participant comfort” and “data quality” in particular when selecting measurement techniques.

Within this framework, the following criteria have been adopted:

Methods identified in neurophysiological measurement techniques

### **Accessibility and Technical Infrastructure Suitability**

- The method should be reasonably available in university/hospital research units,
- Its dependence on specialised, high-cost and rare equipment (such as fully equipped fMRI or PET centres) should be limited.
- The fact that the most commonly used methods in the field of neuroarchitecture, such as EEG, HRV and GSR, are supported by relatively common hardware and software is consistent with this criterion (Rad et al., 2023; Mostafavi et al., 2022).

### **Ease of Application and Integration with VR**

- The measurement system does not physically interfere with VR goggles and head-mounted displays.
- It allows the participant to maintain head, eye, and body movements at a reasonable level.
- The setup and calibration process can be completed within a reasonable time before the experiment.
- Reviews of EEG-VR studies indicate that the use of mobile-portable EEG systems alongside architectural VR experiences is increasingly becoming standard (Taherysayah et al., 2024; Ladakis et al., 2024).

### **Data Quality, Time-Space Resolution and Sensitivity to Targeted Processes**

- The method's sensitivity at the neurophysiological level to the processes the study focuses on (stress, relaxation, mood, attention, perception of spatial comfort, etc.),
- In terms of temporal resolution, it must be able to record at a speed that can accompany scenario transitions and critical spatial moments (e.g., turning towards a specific corner in the room) within VR,
- The existence of established methods and reporting standards in the literature for data analysis.

For example, comprehensive methodological guides by Laborde et al. (2017) for HRV, Boucsein (2012) for GSR, Luck (2014) and Cohen (2014) for EEG provide detailed recommendations on how these techniques can be standardised in psychophysiological research.

### **Participant Comfort, Ethical Compliance, and Safety**

- The method should be non-invasive and cause minimal discomfort to the participant, even during long-term measurements.
- It should not pose additional risks in clinical patient groups (e.g., oncology patients).
- It should be noted that techniques such as fMRI and PET require prolonged immobility and tolerance of enclosed spaces; therefore, they may not always be suitable for chronic patient populations.

### **Cost and Sustainability**

- The costs of device purchase, maintenance, consumables and licensing are at a sustainable level for thesis, research and field application projects,
- The same infrastructure can be reused for future repeatable studies and different VR scenarios.

### **Neurophysiological Measurement Methods Evaluated According to the Specified Criteria**

**Electroencephalography (EEG):** EEG is a method that measures the brain's electrical activity at the millisecond level through electrodes placed on the scalp. Thanks to its high temporal resolution, changes in attention, emotional response transitions, and fluctuations in cognitive load that occur during spatial experiences in VR can be monitored in detail (Luck, 2014; Cohen, 2014).

Systematic reviews of neuroarchitecture and architectural VR studies show that EEG stands out particularly in the following aspects:

- Its use in mapping the effect of architectural forms, colours, lighting patterns, and spatial complexity on brain dynamics,
- Its applicability with VR headsets thanks to portable and wireless systems,
- When combined with machine learning and deep learning approaches, the classification of states such as stress, calmness, satisfaction, or discomfort from EEG patterns (Taherysayah et al., 2024; Jung et al., 2023).

In the context of this study, EEG was selected as one of the fundamental methods to be used in biophilic hospital room scenarios; it will be employed to measure emotional-cognitive load indicators through frontal alpha/beta dynamics, spatial openness-closeness, material and landscape changes across different biophilic levels.

**Heart Rate Variability (HRV):** HRV is an indicator that assesses the activity of the autonomic nervous system, particularly parasympathetic (vagal) activity, based on the analysis of the variability in the time between successive heartbeats. High HRV is generally associated with better physiological flexibility, stress coping capacity, and recovery ability, while low HRV is associated with chronic stress and psychophysiological overload (Shaffer and Ginsberg, 2017; Laborde et al., 2017).

Studies on VR nature experiences and biophilic environments demonstrate that HRV is a powerful biomarker for objectively capturing the stress-reducing effect. In particular, VR nature landscapes and biophilic content have been shown to have positive effects on HRV; that is, users transition to a more physiologically 'relaxed' profile (Kumpulainen et al., 2024; Benz et al., 2022).

For this study, HRV is planned to be measured using mobile chest strap or wristband-based systems to observe differences in physiological stress levels between hospital room scenarios and to evaluate the 'total load created by biophilic parameters' in conjunction with EEG and GSR.

**Galvanic Skin Response (GSR):** GSR is a method that provides information about sympathetic nervous system activity and physiological arousal by measuring changes in skin conductance. Skin conductance tends to increase in situations such as emotional arousal, sudden stress increase, surprise, or anxiety (Boucsein, 2012).

Boucsein's (2012) comprehensive study demonstrates that GSR is one of the most frequently used indicators in psychophysiology and can accurately reflect situations related to stress, anxiety, and attention. In VR-based studies, GSR has been shown to be extremely useful in detecting sudden responses to scenario transitions, unexpected stimuli, and 'disturbing' spatial situations (Kim et al., 2024; Rah et al., 2025).

In this study, GSR is positioned as the third fundamental measurement, alongside EEG and HRV, to capture physiological arousal differences arising in different biophilic hospital room designs and sudden stress responses that may occur in specific spatial configurations (narrow corridors, dark corners, facades without a view, etc.).

**Eye Tracking:** Eye tracking provides detailed information about attention distribution and visual hierarchy by recording the participant's gaze point, saccades (rapid eye movements that enable the eyes to move from one point to another), fixations (when the eyes remain stationary on a point with minimal movement), focus times, and gaze paths. In architectural VR environments, eye tracking is a powerful tool for analysing which elements users notice first in a room, how long they look at which surfaces, and how functional the guidance elements are (Mostafavi et al., 2022).

In the context of this study, eye tracking is considered a complement to the neurophysiological baseline measurement set (EEG–HRV–GSR). For example, if an increase in GSR is observed at a certain point, the eye tracking data will show which spatial element is being looked at at that moment, and when there is an increase in emotional-cognitive load in the EEG, it will be possible to determine more clearly which visual component this occurred simultaneously with. Therefore, eye tracking is particularly important when creating design guidelines, as it directly answers the question of "which biophilic elements are actually noticed and for how long they are experienced".

**Functional Near-Infrared Spectroscopy (fNIRS):** fNIRS is a non-invasive haemodynamic imaging technique that measures changes in oxygenated (HbO) and deoxygenated haemoglobin (HbR) levels on the cortical surface via light sources and detectors placed on the scalp. Thus, brain activity associated with attention, decision-making, and emotional regulation, particularly in the prefrontal and superior cortical areas, can be monitored during relatively natural tasks (Pinti et al., 2018; Quaresima and Ferrari, 2019).

Portable and wearable fNIRS systems allow participants to experience VR scenarios while sitting or standing, enabling the recording of prefrontal oxygenation responses during these activities. In this respect, fNIRS occupies an intermediate position, offering higher motion tolerance than fMRI and better spatial localisation than EEG (Balardin et al., 2017; Pinti et al., 2018). However, multi-channel fNIRS systems are costly and involve additional technical challenges in terms of hair density, optode placement, and signal processing requirements (Quaresima and Ferrari, 2019).

Within the scope of this study, fNIRS holds strong potential for monitoring prefrontal haemodynamic responses in hospital bed experiments equipped with VR-based biophilic design elements; however, due to device procurement, analysis burden, and difficulties in integrating it into clinical practice, it is not included in the basic measurement set (EEG, HRV, GSR); It is discussed as a complementary method for expanded studies that may be conducted in the future.

**Functional Magnetic Resonance Imaging (fMRI):** fMRI is a method that measures changes in blood oxygenation levels in brain regions, imaging brain activity with high spatial resolution. In neuromarketing, neuroaesthetics, and neuroarchitecture studies, fMRI has been used to investigate which cortical and subcortical regions are activated by specific sensory and architectural features (colour, texture, light, smell, form, sound, volume, symmetry, complexity, etc.). However, fMRI is a costly technique that requires subjects to remain in a fixed position for extended periods and only allows VR experiences through limited, stimulus-based protocols.

Rad and colleagues' (2023) systematic review emphasises that fMRI is a theoretically rich but practically and logistically limited tool for experimental studies in the field of architecture. Therefore, in this study, fMRI is not positioned as a fundamental method but as an optional module reserved for future advanced research on specific sub-hypotheses.

**Positron Emission Tomography (PET):** PET is a highly effective method that uses radioactive tracers to visualise metabolic activity, but it is highly invasive and costly. Despite its widespread use in clinical oncology and neurology practice, it does not appear practical as a routine neuroarchitectural measurement tool for VR-based architectural experiments due to reasons such as ethical and radiation safety concerns, the lengthy application time, and its unsuitability for repeated experiments. In Rad and colleagues' (2023) classification, PET is considered a method more suitable for rare, clinically focused studies exploring the relationship between architecture and neuroscience.

Therefore, within the scope of this study, although PET is included in the method selection table, it has been excluded from the basic measurement set recommended for VR-based biophilic hospital room optimisation.

## Conclusion

This study examines the prominent neurophysiological measurement methods in planned neuroarchitectural studies. This table (Table 1) summarises the evaluation of the neurophysiological measurement methods addressed in the study according to the defined criteria, compares them with findings in the literature, and shows their position within the scope of the thesis.

When these criteria are evaluated together, the trio of EEG, HRV, and GSR stands out as the basic measurement set in terms of integration with VR-based biophilic design element-designed bedridden patient room simulations, data quality, cost, and accessibility. Eye tracking is a complementary method; fMRI, fNIRS, and PET are positioned as more limited, advanced complementary or advanced tools around this basic set for specific research questions, as well as within the theoretical framework of fMRI and PET (Rad et al., 2023; Radwan et al., 2025).

**Table 1.** Evaluation of neurophysiological measurement methods (Prepared by the author.)

| Measurement Method | Accessibility and Infrastructure   | VR Integration  | Data Quality and Sensitivity to Target Processes   | Participant Comfort-Ethics  | Cost   |
|--------------------|--|---|--|---|--|
| <b>EEG</b>         | It is relatively common in research laboratories; portable systems may be available. | Compatible with mobile wireless EEG systems that can be used with VR headsets.            | High temporal resolution; sensitive to attention, cognitive load and affective changes.                  | Non-invasive; participant comfort can be managed with appropriate mounting.             | Medium-high; however, it is sustainable with the existing infrastructure in many institutions. |
| <b>HRV</b>         | Relatively common in research laboratories; portable systems may be available.       | It can be used freely during the VR experience; it does not interfere with the head area. | Stress relief is sensitive to the balance of the autonomic nervous system and the capacity for recovery. | Non-invasive and comfortable; generally well tolerated even in clinical patient groups. | Economical for short, medium and long-term studies.  |
| <b>GSR</b>         | There are widely available sensors that are easy to apply                            | There are no issues with simultaneous use with VR; attention must                         | Sensitive to sympathetic arousal and sudden  | Non-invasive; apart from slight discomfort during long                                  | Low; sensor costs are relatively limited.  |

|                     |  |  |   |   |   |
|---------------------|--|--|---|---|---|
|                     | using finger or wrist sensors.   | be paid to motion artefacts.   | stress responses; sensitive to scenario transitions.  | sessions, there are no significant ethical issues.  |   |
| <b>Eye Tracking</b> | Accessibility is increasing with VR glasses integrated systems or external devices.              | It enables real-time tracking of natural gaze behaviour within VR.   | It is sensitive to attention distribution, visual hierarchy and spatial orientation processes.                                  | Non-invasive; well tolerated if the headband is adjusted for comfort.                                 | Medium; variable depending on integrated VR eye-tracking systems. |
| <b>fNIRS</b>        | Portable systems are available; however, they are still limited in number in many organisations. | Can be used with VR; however, head movement and optot placement require attention.   | Sensitive to cognitive load and emotional regulation via prefrontal oxygenation changes; spatial resolution is higher than EEG. | Non-invasive; however, the headband and electrodes require more physical contact.                     | Medium-high; multi-channel systems are relatively expensive.      |
| <b>fMRI</b>         | Only in well-equipped hospitals/research centres; access requires significant infrastructure.    | Limited compatibility with full VR experience; the participant must remain motionless in a narrow tunnel for an extended period. | Very high spatial resolution; however, temporal resolution is limited and ecological validity is low.                           | Non-invasive but confined spaces, noise and prolonged immobility can be challenging for participants. | Very high; equipment and operating costs are high.                |
| <b>PET</b>          | It is located in limited centres requiring high technology; it requires special infrastructure.  | VR integration is practically impossible; movement is severely restricted.   | High sensitivity; however, it is primarily used for metabolic activity and clinical diagnosis.                                  | Due to the use of radiotracers, it is invasive and sensitive in terms of ethics and safety.           | Very high; both the device and processing costs are substantial.  |

**Basic Method:** Taherysayah et al. (2024) systematically reviewed VR–EEG studies, demonstrating that EEG is the most frequently used method for measuring designed environmental experiences. Rad et al. (2023) emphasised the dominant role of EEG in neurophysiological experiments. Jung et al. (2023) analysed the biophilic effect in VR hospital rooms using EEG and machine learning.

Laborde et al. (2017) and Shaffer and Ginsberg (2017) provide detailed guidelines on the use of HRV as an indicator of psychophysiological stress and vagal tone. Kumpulainen et al. (2024) and Benvegnù et al. (2025) demonstrated that VR nature/biophilic content provides physiological relaxation via HRV.

Boucsein (2012) revealed that electrodermal activity is a sensitive indicator of sympathetic arousal. Kim et al. (2024) achieved high sensitivity in stress detection by using GSR and EEG together in a VR interview paradigm, while Rah et al. (2025) modelled VR-centred stress perception using GSR and other biometric indicators.

**Complementary method:** Mostafavi (2022) states in his compilation of biometric and VR-based studies in architecture that the combined use of sensors such as eye tracking, GSR and EEG provides a powerful framework for design evaluation. Eye tracking will bridge neurophysiological findings with spatial perception by revealing whether biophilic elements are actually noticed, which elements are examined for longer periods, and where gaze focus intensifies during moments of stress and relaxation.

**Advanced, complementary method:** Pinti et al. (2018) emphasised the potential of portable fNIRS in monitoring brain function in natural environments, while Balardin et al. (2017) demonstrated the applicability of fNIRS in tasks involving limited freedom of movement. Kaimal et al. (2022) combined VR and fNIRS to show that prefrontal activity changes depending on emotional/creative task types. Due to infrastructure and cost, fNIRS has not been included in the core method set; however, it has been positioned as a potential area for future expansion to examine the prefrontal haemodynamic signatures of biophilic hospital room scenarios.

**Theoretical reference:** Kühn et al. (2017) examined the relationship between enriched environmental features and brain structure using fMRI, discussing the concept of an 'enriched environment' at the neurobiological level. Rad et al. (2023) note in their systematic review of neuroarchitectural experimental studies that, despite fMRI's high spatial accuracy, its use is limited due to ecological validity and logistical difficulties. fMRI has limitations in terms of applicability because it requires both healthy and ill participants to be in relatively natural positions in a VR environment. However, it contains noteworthy data within the theoretical framework.

PET, while a powerful clinical tool for examining brain metabolism, is not recommended for VR-based architectural/neuroarchitectural experiments due to radiation exposure, cost, and movement constraints. Therefore, although it is considered a theoretical reference representing only one end of the neuroimaging spectrum in neuroarchitectural research, it is not included in the scope of application.

The data obtained from this study contributes to the theoretical and practical framework regarding which method(s) can be used in neuroarchitectural research, particularly in the process of optimising space through artificial intelligence integration.

In this regard, machine learning and design optimisation processes will follow VR-based neurophysiological measurements. For example, for biophilic design parameters (light, colour, form, material, plant density, etc.), there will be EEG, HRV, GSR indicators and mood-stress-satisfaction scores. A composite well-being score representing the 'improving response' will be defined in the VR-based neurophysiological measurement process; the model will suggest new space combinations that maximise this score. Feature importance analyses will determine which biophilic parameters are associated with lower physiological stress, more balanced neurophysiological responses, and higher spatial satisfaction, and these will be converted into decision rules for the neurobiophilic-neuroarchitectural design guide (Jung et al., 2023; Bulaj et al., 2025).

In optimisation scenarios, for example, when a designer inputs the question, 'Window location fixed, cost limited; what is the colour-material-plant combination that provides the highest well-being score?' into the system, the model will suggest the most likely 'healing' design alternatives based on the relationships it has learned from past data.

Additionally, as a result of these analyses, a preliminary definition of the 'neurobiophilic healing parameter area' for inpatient rooms can be established; that is, it will be possible to computationally demonstrate which biophilic components should be included in the patient room design and within which ranges (e.g., minimum nature visibility, optimal wood ratio, daylight threshold) to be most advantageous from a physiological and psychological perspective. This approach is also consistent with the parameter framework proposed by Tekin and colleagues for biophilic healthcare structures (Tekin et al., 2023; Tekin, 2025).

Finally, when the outputs of artificial intelligence analyses are structured in the form of a design guide, they are expected to generate concrete recommendations such as the following:

'If there is no direct view of nature in the room, an increase of x level in HRV is predicted with this level of VR-supported digital nature and this type of indoor greening.'

"This combination (daylight, wood textures, ceiling height, plant density) appears to be associated with the lowest stress profile according to EEG and HRV data."

"Maintaining the lighting colour temperature within this range is more advantageous in terms of mood, especially in the evening hours."

Such outputs have the potential to become a tool that supports the human-centred health space concept developed by Tekin and colleagues through Maggie's centres with numerical data and provides decision support to designers (Tekin et al., 2023; Tekin, 2023).

### **Interior Space Model and VR Scenarios Prepared with Biophilic Design Elements**

Neurophysiological measurements will be taken during a VR experience based on a three-dimensional model of hospital patient rooms in healthcare facilities. This model includes:

- Light (daylight ratio, brightness level, colour temperature),
- Colour (warm-cool tones, saturation, contrast),
- Materials (natural-wood, stone, neutral synthetic surfaces),
- Plant-natural elements (plant density, location, type),
- Landscape (trees-green areas, urban facades, inner courtyards, etc.),

Spatial qualities (ceiling height, openness–enclosure, visual complexity, etc.) will be systematically varied as biophilic design parameters (Ryan et al., 2014; Al Khatib et al., 2024).

During neurophysiological measurements, at least three levels of biophilic scenarios will be proposed.

• **Low biophilic level:** Limited plants/green elements, neutral colours, low use of natural materials, limited views.

• **Medium biophilic level:** Limited but noticeable plants, wood/natural textures, emphasis on daylight, limited external views.

• **High biophilic level:** Abundant plant life, heavy use of natural materials, views of nature, high daylight, warm colour palette.

In the production of scenarios, design principles derived from contemporary biophilic hospital examples (e.g., Maggie's Centres, Princess Máxima Centre, Ostra Psychiatric Clinic) will also be utilised to create spatial recognition and a realistic hospital context for the user. (Jencks and Heathcote, 2010; Tekin et al., 2023; van der Linden, 2016).

A high-resolution head-mounted display (HMD) will be used for the VR application; a short navigation scenario involving controlled guidance will be designed to give participants the feeling of 'walking' within the space (You et al., 2023; Kumpulainen et al., 2024).

### **Contributions to Neuroarchitecture and Healthcare Facility Design**

The neuroarchitecture literature has conceptualised the effects of architectural features on brain networks and cognitive-emotional processes; however, it emphasises that systematic neurophysiological protocols are still limited at the scale of healthcare facilities (Abbas et al., 2024; Rad et al., 2023; Tekin, 2025). This study, with its method devised along the VR–EEG–HRV–GSR axis:

aims to relate neuroarchitecture not only at a conceptual level but also to an empirically testable design decision system in critical healthcare spaces such as inpatient wards.

In this sense, one of the most significant contributions of the study is that it presents a framework integrating the triad of spatial parameters-neurophysiological response-artificial intelligence decision support. This framework both strengthens the evidence-based design approach and makes neuroarchitecture an applicable tool specifically for healthcare structures (Miola et al., 2025; Bulaj et al., 2025).

## **Implications for Clinical and Design Practice**

Inpatient wards, particularly in units such as oncology, internal medicine, or chronic disease wards, are places where patients are confined to enclosed spaces for days or weeks. When the framework proposed in this study is implemented:

- In new hospital buildings at the project stage,
- In existing wards undergoing renovation,

it will be possible to make design decisions based not only on regulations and functionality, but also on sets of 'healing' parameters defined by neurophysiological data (Tekin et al., 2023; Tekin, 2023).

VR-based neurophysiological measurement methods integrated with artificial intelligence are expected to provide the following concrete contributions to the spatial optimisation process:

For example, "in this service, if VR-supported biophilic content and indoor greening are applied together for rooms without a view of nature, the expected stress-reducing effect is at level X."

'Increasing the proportion of wood materials in this corridor and not lowering the ceiling height below this threshold is advantageous in terms of neurophysiological calmness indicators.'

Therefore, the proposed system offers a framework conducive to collaboration between architects, interior designers, healthcare managers, and physicians through concrete measurements and AI-supported simulations.

## **Methodological Contribution: VR, Multi-Biomarker and AI Integration**

Rad and colleagues' (2023) systematic review, while classifying measurement techniques used in neurophysiological experiments, notes that the combination of VR+EEG+physiological indicators is increasingly prominent, but there are still very few examples in the context of healthcare structures and biophilic design. This study:

- is methodologically unique in its combination of:
- grounding VR representations in real hospital typologies,
- integrating multiple biomarkers such as EEG, HRV, GSR (and, at an advanced level, fMRI/PET),
- aiming to translate outputs directly into design guidance.

In this respect, it proposes a reusable methodological template not only for this specific project but also for future neuroarchitecture research.

## **Limitations and Future Work**

This framework has some important limitations:

### **VR–real-world Equivalence:**

Although VR experiences can produce a high level of emotional equivalence with real-world experiences (Kobayashi et al., 2025), modalities such as touch, temperature, and smell remain limited. Further studies comparing real-world experiences with VR outcomes are required.

### **Sample Diversity:**

Working with healthy volunteers in the initial phase will create limitations when transitioning to patient populations. In subsequent phases, it is important to conduct clinical studies involving real patient groups in oncology, cardiology, etc. (Tekin et al., 2023; Bulaj et al., 2025).

### **Technological and Ethical Constraints:**

Advanced imaging techniques such as fMRI and PET can only be applied in specific centres, at high cost and under strict ethical conditions. Therefore, these methods are recommended as optional, advanced-level modules.

Before commencing studies using neurophysiological measurement methods, ethical committee approval must be obtained; participants will be informed about the process, potential risks (e.g., dizziness in VR), and their rights, and written consent will be obtained. All data will be stored anonymously and used solely for scientific purposes; as neurophysiological recordings constitute

personal health data, they will be protected in accordance with the Personal Data Protection Law (KVKK) and relevant ethical regulations.

### **Generalisation**

The parameter space to be obtained will be generated according to a specific cultural and spatial context (e.g., a university hospital in Turkey). In different cultures and climates, the weights of 'healing' biophilic components may vary (Tekin, 2025; Deniz, 2025).

Future studies comparing neurobiophilic design across different climate zones, cultural backgrounds, and user groups will increase the generalisability of this framework.

### **General Conclusion**

The framework proposed in this article aims to develop an evidence-based interior design guide for inpatient services by combining the neuroarchitecture approach, biophilic design principles, VR-based neurophysiological measurements, and artificial intelligence analytics. Although biophilic hospital design, examples of healing architecture such as Maggie's Centres, and the physiological effects of VR nature experiences have been examined separately in the literature (Ulrich, 1984; Tekin et al., 2022; Miola et al., 2025; Kumpulainen et al., 2024), studies that integrate these components into a single, holistic design decision system are extremely limited.

The data obtained from neurophysiological measurements during the simulation process using VR technology, as proposed by Sozer (2023), provides a powerful tool for optimising spaces and examining architectural spaces in a human-centred manner through an agent-based modelling system, which is an artificial intelligence software. In this context, it is important to determine the suitability of which neurophysiological measurement method or methods are generally appropriate according to the criteria of 'field applicability,' 'participant comfort,' and 'data quality.' The neurophysiological measurement methods highlighted in this study are instructive in theory and practice in the neuroarchitecture approach.

### **This Enables the Following During the Architectural Design Phase:**

- Different spatial configurations can be tested in a virtual environment,
- During this experimentation, responses such as cognitive and emotional reactions, stress levels, and focus can be measured.
- Human movement, circulation flow, and behaviour patterns can be predicted using machine learning,
- Design decisions can be optimised based on 'human-space interaction' data.

### **Furthermore, with this Proposed Method;**

- Each user (patient, visitor, staff, etc.) is modelled as a factor,
- How these agents move within the space,
- How they respond to stimuli (light, crowds, signage, doors, corridors, waiting areas, etc.),
- In which scenarios congestion, stress, disorientation, or circulation problems arise can be tested through simulation.

In summary, the integration of data obtained from the simultaneous measurement of VR-based spatial simulations using neurophysiological techniques into factor-based artificial intelligence modelling enables the simulation of human behaviour in architectural spaces within a computer environment. This provides a scientific and simulation-based answer to the question, 'How do people actually behave in this space?' When implemented, the proposed method will enable architectural decisions in hospital design to be based not only on normative or architectural standards, but also on user-centred and neurobiophilic parameters that are validated by brain and body responses, in other words, focused on the interaction between brain, body and space. This has the potential to provide a new and robust evidence-based foundation for both healthcare facility design and neuroarchitecture theory.

## References

- [1] Abbas, S., Okdeh, N., Roufayel, R., Kovacic, H., Sabatier, J.-M., Fajloun, Z., and Abi Khattar, Z. (2024). Neuroarchitecture: How the perception of our surroundings impacts the brain. *Biology*, 13(4), 220. <https://doi.org/10.3390/biology13040220>
- [2] Al Khatib, I., Samara, G., and Ndiaye, A. (2024). A systematic review of the impact of therapeutical biophilic design on health and well-being in healthcare facilities. *Frontiers in Built Environment*, 10, 1467692. <https://doi.org/10.3389/fbuil.2024.1467692>
- [3] Benz, E., et al. (2022). Built environment color modulates autonomic and EEG responses in virtual reality. *Psychophysiology*, 59(12), e14112.
- [4] Boucsein, W. (2012). *Electrodermal activity* (2nd ed.). Springer.
- [5] Chatterjee, A., and Vartanian, O. (2014). Neuroaesthetics. *Trends in Cognitive Sciences*, 18(7), 370–375.
- [6] Chatterjee, A., Coburn, A., and Weinberger, A. (2021). The neuroaesthetics of architectural spaces. *Cognitive Processing*, 22(1), 115–120.
- [7] Cohen, M. X. (2014). *Analyzing neural time series data: Theory and practice*. MIT Press.
- [8] Higuera-Trujillo, J. L., Llinares, C., and Macagno, E. (2021). The cognitive-emotional design and study of architectural space: A scoping review of neuroarchitecture and its precursor approaches. *Sensors*, 21(6), 2193. <https://doi.org/10.3390/s21062193>
- [9] Jencks, C., and Heathcote, E. (2010). *The architecture of hope: Maggie's Cancer Caring Centres*. Frances Lincoln.
- [10] Kumpulainen, S., Hauru, K., Tyrväinen, L., and Korpela, K. (2024). Assessing the well-being benefits of VR nature experiences: Heart rate variability insights from a cross-over study. *Journal of Environmental Psychology*, 97, 102366.
- [11] Laborde, S., Mosley, E., and Thayer, J. F. (2017). Heart rate variability and cardiac vagal tone in psychophysiological research-Recommendations for experiment planning, data analysis, and data reporting. *Frontiers in Psychology*, 8, 213.
- [12] Ladakis, I., Filos, D., and Chouvarda, I. (2024). Virtual reality environments for stress reduction and management: A scoping review. *Virtual Reality*, 28, 50. <https://doi.org/10.1007/s10055-024-00943-y>
- [13] Luck, S. J. (2014). *An introduction to the event-related potential technique* (2nd ed.). MIT Press.
- [14] Miola, L., Boldrini, A., and Pazzaglia, F. (2025). The healing power of nature: Biophilic design applied to healthcare facilities. *Current Opinion in Psychology*, 52, 102049. <https://doi.org/10.1016/j.copsy.2025.102049>
- [15] Mostafavi, A., et al. (2022). Architecture, biometrics, and virtual environments: A review of methods for studying built environments and human experience. *Architectural Science Review*, 65(6), 567–582. <https://doi.org/10.1080/00038628.2021.2008300>
- [16] Pinti, P., Aichelburg, C., Gilbert, S., Hamilton, A., Hirsch, J., Burgess, P. W., and Tachtsidis, I. (2018). A review on the use of wearable functional near-infrared spectroscopy in naturalistic environments. *Japanese Psychological Research*, 60(4), 347–373. <https://doi.org/10.1111/jpr.12206>
- [17] Quaresima, V., and Ferrari, M. (2019). Functional near-infrared spectroscopy (fNIRS) for assessing cerebral cortex function during human behavior in natural/social situations: A concise review. *Organizational Research Methods*, 22(1), 46–68. <https://doi.org/10.1177/1094428116658959>
- [18] Rad, P. N., Behzadi, F., Yazdanfar, S. A., Ghamari, H., Zabehe, E., and Lashgari, R. (2023). Exploring methodological approaches of experimental studies in the field of neuroarchitecture: A systematic review. *HERD: Health Environments Research and Design Journal*, 16(2), 284-309. <https://doi.org/10.1177/19375867221133135>
- [19] Radwan, A., Mohammed, M. A. E., and Mahmoud, H. (2025). Review of biometric sensors for assessing human emotional responses in virtual reality architectural studies. *JES: Journal of Engineering Sciences*, 53(3), 288–305. <https://doi.org/10.21608/jesaun.2025.354434.1415>
- [20] Rah, A., et al. (2025). Virtual reality centric stress detection using dynamic behavioral and physiological signals. *Electronics*, 14(22), 4501.
- [21] Shaffer, F., and Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. *Frontiers in Public Health*, 5, 258. <https://doi.org/10.3389/fpubh.2017.00258>
- [22] Sözer, E. (2020). "Nöromimari" yaklaşımı ve hastane yapılarındaki mekânsal öğelerin kullanıcılar üzerindeki etkisinin incelenmesi [Yüksek lisans tezi, Karabük Üniversitesi]. YÖK Ulusal Tez Merkezi.
- [23] Sozer, E. (2023a). *Neuroarchitecture: Perception games*. Vadi Publishing House.
- [24] Sozer, E. (2023b). *Neuroarchitecture: Brain conversations*. Vadi Publishing House.
- [25] Sozer, E. (2023c). *Neuroarchitecture Metamorphosis-Healing Spaces*. Vadi Publishing House.
- [26] Sozer, E., and Turcan, Y. (2022). The "Neuroarchitecture" approach and the impact of spatial elements in hospital buildings on users. *Düzce University Journal of Science and Technology*, 10(2), 991-1005. <https://doi.org/10.29130/dubited.961458>
- [27] Taherysayah, F., Malathouni, C., Liang, H. N., and Westermann, C. (2024). Virtual reality and electroencephalography in architectural design: A systematic review of empirical studies. *Journal of Building Engineering*, 85, 108611. <https://doi.org/10.1016/j.job.2024.108611>
- [28] , B. H., Corcoran, R., and Urbano Gutiérrez, R. (2023). A systematic review and conceptual framework of biophilic design parameters in clinical environments. *HERD: Health Environments Research and Design Journal*, 16(1), 233-250. <https://doi.org/10.1177/1937586721995077>

- [29] Tekin, B. H., Corcoran, R., and Urbano Gutierrez, R. (2023b). The impact of biophilic design in Maggie's Centres: A meta-synthesis analysis. *Frontiers of Architectural Research*, 12(4), 791-808. <https://doi.org/10.1016/j.foar.2023.05.005>
- [30] Ulrich, R. S. (1984). View through a window may influence recovery from surgery. *Science*, 224(4647), 420-421. <https://doi.org/10.1126/science.6143402>
- [31] Ulrich, R. S. (1999). Effects of gardens on health outcomes: Theory and research. In C. C. Marcus and M. Barnes (Eds.), *Healing gardens: Therapeutic benefits and design recommendations* (pp. 27-86). John Wiley and Sons.