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Review article

A review of the effectiveness of metrics for assessing human responses to biophilic environments involving views, shading, and interior design elements

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ABSTRACT

The characterization of biophilic environments, recognized for their potential to enhance well-being, requires researchers to have access to relevant metrics and methodologies when it comes to assessing this potential. Given the large diversity of well-being measures and experimental protocols used in existing studies, this review aims to critically evaluate the effectiveness of well-being metrics and measures that have been proposed or investigated in the literature with a focus on views, shading, and interior design elements. These include subjective, physiological, and cognitive metrics, as well as a diversity of experimental protocols used in studies on biophilic interventions indoors. The review analyzes the distribution of selected experimental stimuli, context, environment, and setup, with special attention given to identifying and analyzing metrics associated with well-being outcomes that demonstrated statistical significance. Additionally, this paper highlights the underreported aspect of effect size, which is systematically compiled and presented here. The purpose of this review is to provide a comprehensive understanding of the metrics used in the biophilic environment research of indoor spaces so far and to offer a grounded framework for future studies aiming to evaluate the impact of biophilic interventions on occupant well-being.

Contents

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1. Introduction

Connecting with nature profoundly and positively impacts human well-being. Numerous studies have linked exposure to natural environments to reduced stress levels (Kaplan & Talbot, 1983; Ulrich et al., 1991), improved mood, physical health (Maas et al., 2006), and better cognitive function (Berman et al., 2008; Kaplan & Berman, 2010). Modern urban lifestyles have, in parallel, led people to spend most of their time indoors (Diffey, 2011; Klepeis et al., 2001), i.e. in interior environments that often lack natural elements, which tends to exacerbate the disconnection from nature (Wolch et al., 2014). This disconnection has been associated with a range of negative health outcomes, including increased stress, negative emotion (Berto, 2014), and reduced cognitive function (Mason et al., 2022).

The term biophilia, popularized by Edward O. Wilson (Wilson, 1984), refers to humans' inherent affinity for nature. Biophilic design expands on this concept by integrating natural elements into design to enhance well-being. One prominent biophilic design framework identifies 14 patterns of environmental features organized into three distinct categories: Nature in the Space (direct experiences of natural elements), Natural Analogues (indirect references to natural forms and patterns), and Nature of the Space (spatial configurations that evoke natural environments) (Browning et al., 2014).

Many reviews have explored different aspects of biophilic design within indoor environments. Although some articles have examined multisensory aspects of biophilic elements including, visual, auditory, thermal and air quality factors (Ríos-Rodríguez et al., 2023; Yildirim et al., 2023), visual aspects remain the most frequently studied. This focus is largely due to their direct relevance to architectural design and significant impact on well-being (Gillis & Gatersleben, 2015). Topics commonly covered include indoor plants (Han & Ruan, 2019; Liu et al., 2022), indoor lighting (Karaman Madan et al., 2024; Kong et al., 2022b), interior materials (Zhao et al., 2023), views (Farley & Veitch, 2001) and views along with lighting and daylighting within buildings (Vasquez et al., 2022a, 2022b). However, despite numerous reviews exploring individual visual elements of biophilic design, there remains a lack of comprehensive synthesis that brings these elements together to evaluate their combined, interactive, and comparative impacts on human responses. This review aims to fill this gap by critically examining the experiments and measures employed across various visual biophilic studies, with an emphasis on identifying and comparing metrics that have been linked to statistically significant effects on human well-being.

To do so, we focus on three core visual biophilic features – views, shading, and interior design elements – which fall under the broader categories of visual connection to nature and natural analogues within the biophilic design framework (Browning et al., 2014). These elements contribute to the visual richness of indoor environments and have been linked to various well-being benefits. Views to the outside, providing a direct visual connection with nature, have been associated with improved mood and reduced stress (Du, 2022; Li, 2016; Lin et al., 2022; Tennessen & Cimprich, 1995). Shading and light patterns – particularly those inspired by natural forms – can replicate the dynamic lighting of outdoor settings, supporting comfort and productivity (Abboushi et al., 2019; Chamilothori, Lemmens, et al., 2022; Chamilothori et al., 2022c). Meanwhile, interior design elements like wood finishes and greenery offer restorative effects even in the absence of direct outdoor access (Lan & Liu, 2023; Lei et al., 2021; Li, 2022; Tsunetsugu et al., 2007; Yeom, 2021).

Well-being outcomes in biophilic environment research are typically assessed through three main types of dependent variables: subjective, physiological, and cognitive measures (Hartig et al., 2014). We systematically reviewed how these metrics have been applied and analyzed, and evaluated their sensitivity in detecting significant effects across different experimental conditions. Our review also considered the nature of experimental stimuli, the contexts in which they were implemented, the simulation of virtual environments where applicable, and the overall structure of the experimental setups. In addition, we placed particular emphasis on the often under-reported aspect of effect size, which we systematically extracted from all eligible studies for dedicated analysis and discussion.

2. Methodology

The main objective of the review is to understand the current state-of-the-art when it comes to well-being metrics for human responses in studies of biophilic environments on the one hand, and to pinpoint the most effective metrics and methods for assessing well-being outcomes on the other. To achieve this, we performed an extensive search for eligible literature with a focus on the metrics considered so far to assess human responses that would broadly pertain to well-being in biophilic environments. The review process adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al., 2021) to ensure a transparent and systematic approach.

2.1. Search strategy

The initial search was carried out in two major bibliographic databases: Scopus and Web of Science. Literature published from 1995 to 2023 was considered, with the final search executed in December 2023. The search terms were derived through a structured approach consisting of two steps: (1) referencing established biophilic design frameworks (Browning et al., 2014), specifically focusing on the visual connection with nature and natural analogues; and (2) analyzing representative related studies (Chamilothori, et al., 2022; Douglas et al.,

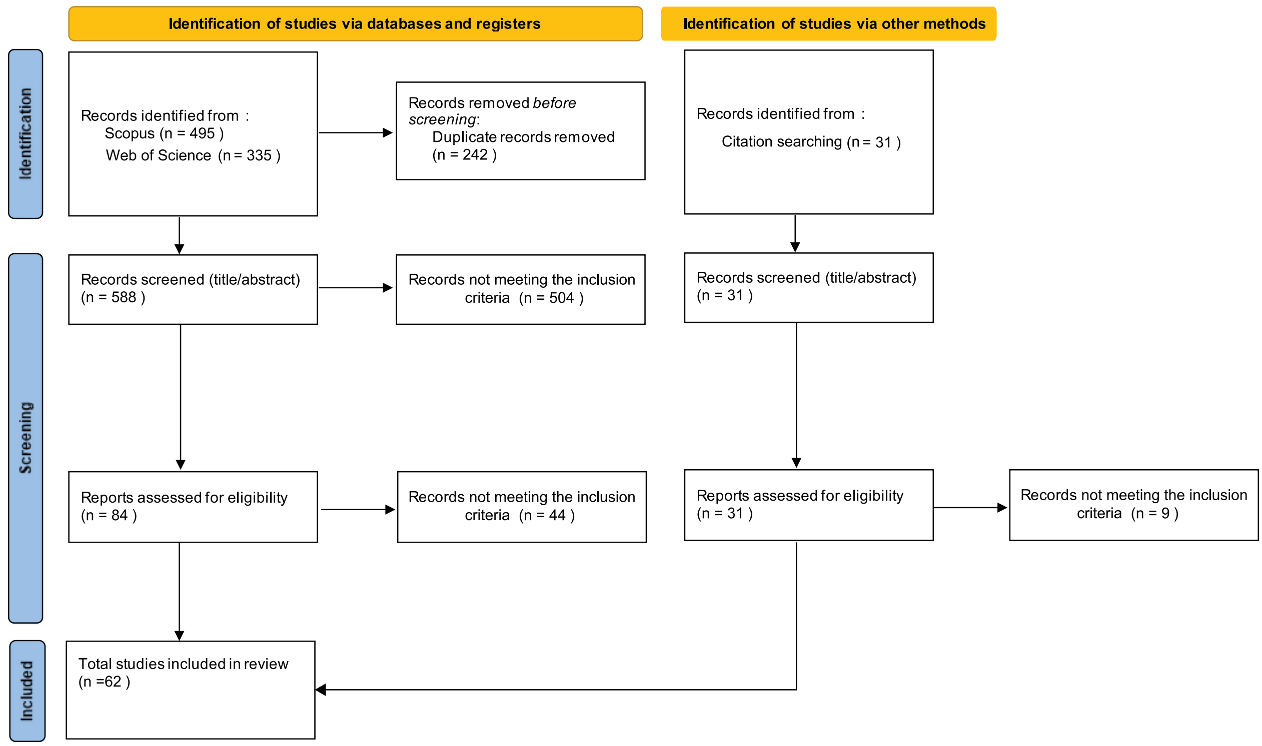

Fig. 1. PRISMA flow diagram of study selection and identification.

Table 1
List of key words.

Subset	Keywords
Intervention	"biophilic design" OR "window view" OR "window access" OR "views to nature" OR "shading patterns" OR "light patterns" OR "daylight patterns" OR "sunlight patterns" OR "dappled light" OR "facade patterns" OR "green wall" OR "indoor greenery" OR "indoor plant" OR "contact with wood" OR "natural elements" OR "virtual plants" OR "wooden indoor environments" OR "wooden material" OR "wooden materials"
Context	architecture OR room OR indoors OR interior OR office OR workplace OR classroom OR hospital OR dormitory
Outcome	"well-being" OR wellbeing OR "human response" OR restoration OR stress OR mood OR emotion OR perception OR psychological OR subjective OR physiological OR "cognitive performance" OR attention

2022; Yin et al., 2019, 2020) to extract additional key terms. The identified keywords were grouped into three subsets (Intervention, Context, Outcome), summarized in Table 1. These subsets were combined using Boolean operators ('OR' within subsets, 'AND' between subsets), and searches were conducted in the title and abstract fields.

Initial inclusion criteria were defined as follows: (1) peer-reviewed journal articles or conference proceedings; and (2) publication dates between 1995 and 2023. The search and selection procedure is outlined in the PRISMA flow diagram in Fig. 1. A total of 495 records were retrieved from Scopus and 335 from Web of Science. After removing 242 duplicates, 588 records remained for the first screening. The process was facilitated using an Excel spreadsheet containing title, authors, and abstracts for each source. Any disagreements during screening were resolved through discussion between the authors.

Inclusion and exclusion criteria were defined using the PICO (Population, Intervention, Comparator, Outcome) framework (Schardt et al., 2007), detailed in Table 2. Specifically, the review targeted studies examining immediate human responses in controlled indoor environments, focusing on three types of responses: subjective (self-reported psychological states), physiological (bodily measures), and cognitive (task-based performance assessments). The scope explicitly excluded studies investigating long-term effects, such as sustained health recovery or prolonged learning outcomes. Biophilic interventions included visual features of nature (e.g., window views, biophilic shading and resulting daylight patterns, or nature-inspired interior design elements such as indoor plants or wooden finishes). Studies were required to report quantitative outcomes with statistical measures of significance (e.g., p-values), excluding review articles and purely qualitative research.

After title and abstract screening, 84 articles remained for full-text review. An additional 31 records were identified through citation tracking via reference list checks, bringing the total to 115 studies for full-text assessment. Following this stage, 53 papers that did not meet the inclusion criteria were excluded, resulting in 62 records for detailed review.

2.2. Data extraction

For each study included in the review, relevant data were systematically extracted into a structured Microsoft Excel spreadsheet. Key aspects of the protocol were collected, such as the number of independent variables, participant count, experimental design (within-subject or between-subject), and duration of the experiment. Beyond these general descriptors, the data extraction process was designed to align with our main objective: identifying robust metrics and methods for evaluating human well-being outcomes associated with biophilic environments. Specifically, detailed information was collected regarding the stimuli evaluated, the contexts and characteristics of the biophilic environments, experimental setup specifics, and the human responses (and thus the chosen well-being metric). Additional relevant details were also documented when applicable, such as the presence of natural landscapes in window views, type of shading and light patterns (regular or biophilic), and specifics regarding indoor design elements (e.g., green wall coverage percentage or extent of wood finishes).

Table 2
PICO and eligibility criteria.

PICO	Inclusion Criteria	Exclusion Criteria
Participants	Studies with human participants	Studies without human participants
Intervention	Studies with variation in biophilic features (e.g., window views, shading and light patterns, interior design elements) in indoor environments	No biophilic variation; non-indoor settings; uncontrolled confounds
Comparators	No specific comparator required	
Outcomes	Quantitative measures of subjective, cognitive, or physiological response	No statistical analysis; qualitative only; unrelated or long-term outcomes

The studies reviewed spanned three primary experimental contexts – rest (e.g., dormitory rooms or lounge spaces), work (e.g., offices or classrooms), or social interactions (e.g., cafés or communal areas) – and were conducted in physical environments (controlled room setups), virtual environments (utilizing VR, screens, projections, or paper-based imagery), or hybrid (mixed) environments. Outcome metrics from each study were grouped into three categories consistent with our analytical framework: subjective psychological responses, cognitive performance, and physiological responses. For the subjective outcomes, to enhance comparability and specificity, we emphasized individual metrics rather than broad composite indices. For instance, aggregated scores from instruments such as the Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988), the State-Trait Anxiety Inventory (STAI) (Spielberger et al., 1983), or the Profile of Mood States (POMS) (McNair et al., 1971) were broken down into individual affective dimensions or specific mood states whenever possible.

Several studies conducted multiple statistical tests without adjusting their significance thresholds, which increases the risk of false positives. Only a small number applied correction methods, such as the Bonferroni (Dunn, 1961) or Bonferroni–Holm (Holm, 1979) adjustments, which are designed to control for Type I errors in multiple comparisons. Within the list of reviewed papers, seven biophilic studies that included multiple tests (Abboushi et al., 2021; Chamilothori et al., 2019; Chamilothori, et al., 2022; Chamilothori et al., 2022c; Du, 2022; Ko et al., 2023, 2020; Kong et al., 2022) did consider the issue and adjusted the threshold for significance. However, all the other reviewed articles simply used the default significance threshold of 0.05 (Fisher, 1970) despite the presence of multiple tests, which could potentially affect their respective conclusions. As it was not possible to redo these studies' statistical analyses with adjusted significance thresholds, we had to rely on the statistical significance declared in the articles for the purposes of this review, but would recommend a more detailed examination of the findings coming from these papers before considering them as a basis for future research.

A further caution relates to effect size, discussed in Section 7. Despite its importance in assessing the practical impact of biophilic interventions and informing appropriate sample sizes (Ferguson, 2009), many studies did not report effect sizes. To support future research, the effect sizes available were compiled in Tables 5, 6, and 7.

3. Analysis of experimental approaches

Our review seeks to pinpoint the most effective metrics and methods for evaluating well-being outcomes within biophilic environments. This section explores the results by focusing on two key areas: experimental protocols and well-being measures, detailed in Sections 3.1 and 3.2, respectively. By examining the experimental protocols, including the types of stimuli used, the contexts in which experiments were conducted, and the environments in which these studies took place, we aim to provide readers with insight into how studies are commonly designed and conducted. On the other hand, our analysis of well-being measures focuses on assessing the significance and effect size of subjective well-being, physiological health, and cognitive function. Through this analysis, our objective is to provide a comprehensive understanding of the effectiveness of these measures in assessing the impact of biophilic environments on the occupants.

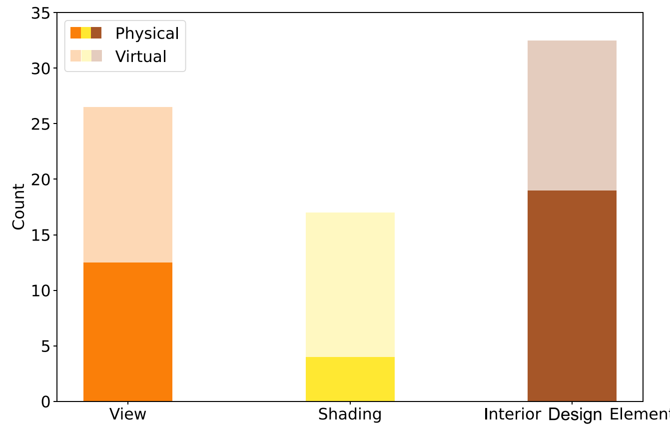

Fig. 2. Investigated stimuli.

3.1. Experimental protocols

Human-centric experiments in biophilic environments vary widely, and understanding the different dimensions of these experiments is essential for our review. By examining the types of stimuli discussed in Section 3.1.1, we aim to identify which stimuli have been thoroughly investigated and which require further study. This helps us to determine the effectiveness of different biophilic elements in promoting well-being outcomes.

Similarly, exploring the contexts described in Section 3.1.2 allows us to understand the specific situations in which biophilic interventions have been tested. This information helps us assess the generalizability of the findings and identify potential trends associated with specific contexts.

Furthermore, by analyzing the environmental settings in which these experiments have been carried out, as described in Section 3.1.3, we can gain insight into the feasibility and practicality of implementing biophilic interventions.

Lastly, examining the experimental setups detailed in Section 3.1.4 allows us to understand the relationship between the duration of the experiment, the number of independent variables, the number of participants and the types of experimental designs. This helps us to determine the reliability and validity of the experimental setups and to offer some guidance for future research in this field.

3.1.1. Stimuli

To get information on the extensively studied stimuli, Fig. 2 presents a bar graph illustrating the distribution of the stimuli in the papers reviewed. The shade of color represents whether the experiment is conducted in physical or virtual environments. The x-axis shows the three categories of stimuli: views, shading (e.g. shading and light patterns), and interior design elements (e.g. indoor greenery, wood finish, nature audio, and furniture in biophilic patterns). The y-axis shows the number of papers that investigated each stimulus.

The graph reveals that interior design elements were the most frequently studied stimuli, with 19 papers exploring this question in

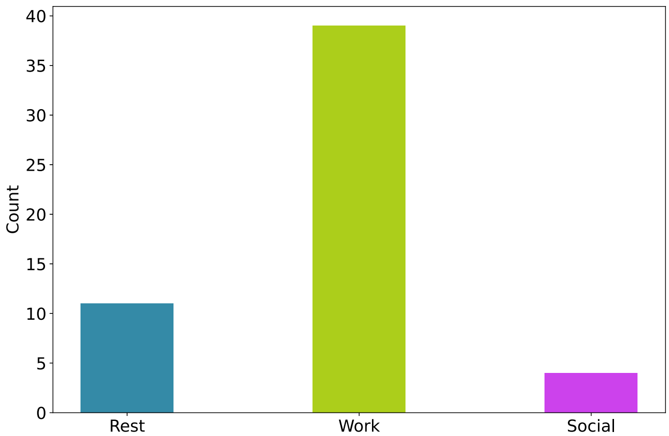

Fig. 3. Chosen occupancy contexts.

physical settings and 13.5 papers in a virtual setting instead. Views were investigated in physical environments by 12.5 studies and in virtual environments by 14 studies, while the exploration of shading and light patterns was less frequent and was conducted primarily in virtual environments, with 13 studies compared to only 4 physical studies.

This limited focus on shading and light patterns may be partly due to the relatively recent emergence of biophilic shading and dynamic light as research topics in environmental design; in addition, the utilitarian framing of conventional shading systems – such as venetian blinds or textile shades, typically intended for thermal or visual comfort (European Committee for Standardization, 2005) – may have led researchers to overlook their biophilic potential. This represents a significant research gap, particularly given the well-documented benefits of natural daylighting and daylight patterns. Natural daylight has been shown to improve mood, boost productivity, enhance cognitive function, and regulate circadian rhythms (Boubekri et al., 2014; Münch et al., 2020). On the other hand, effective shading strategies play a crucial role in filtering daylight, preventing discomfort while still providing illumination. This not only allows occupants to reap the benefits of daylight but also contributes to energy savings (Tzempelikos & Athienitis, 2007). Particularly, biophilic shading, which incorporates nature-inspired elements, may offer additional benefits such as stress reduction, improved well-being, and increased connection to nature (Abboushi et al., 2021; Chamilothori, et al., 2022). The relative scarcity of papers or reviews on shading and light patterns highlights the need for more work in this area.

3.1.2. Context

Exploring contexts is essential to understand the applicability and generalizability of research findings. Fig. 3 shows that when it comes to the chosen contexts (Rest, Work, and Social) and their distribution among the studies, the work context is by far the most dominant, accounting for 39 studies. The context of “Rest” was chosen in 11 studies, and the Social context only in 4 studies. The imbalance in research focus across contexts reflects the growing interest in optimizing workplace design for productivity, well-being, and employee satisfaction, likely driven by workplace stress and fatigue (Teasdale, 2006; Vischer, 2007), which has prompted research on biophilic design to mitigate these effects and enhance supportiveness (Chen & Lin, 2024; Hähn et al., 2021; Lei et al., 2021). On the other hand, the relatively limited exploration of social and rest contexts represents both a notable gap and a promising opportunity for future research. Rest and social areas offer very valuable opportunities for restoration, and incorporating biophilic design principles into these spaces could significantly enhance their restorative potential (Hasa & Husein, 2023; Wen et al., 2025) while also indirectly benefiting work environments by promoting a more effective recovery from occupational stress.

3.1.3. Environment

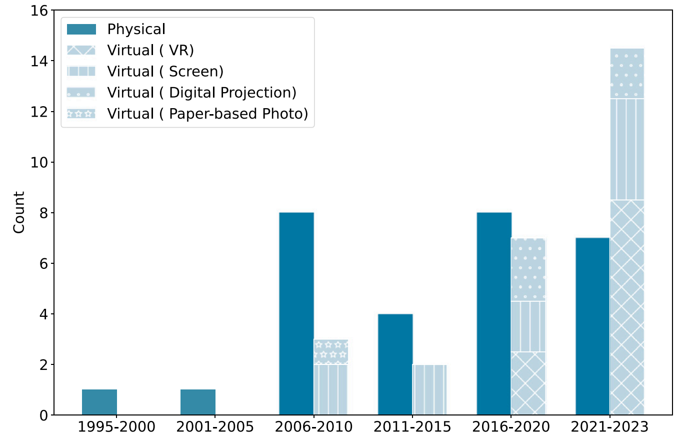

Fig. 4. Experimental environments over the years.

Since 2010, biophilic research has increasingly shifted from physical to virtual environments, as shown in Fig. 4. This transition reflects the growing interest and advancements in virtual environment applications. Within the virtual environments (light blue bars), four distinct hatches represent specific technologies used: crosses for VR, vertical lines for screens, dots for digital projections, and stars for paper-based photos. These allow us to reveal that around 2010 (from 2006 to 2015), researchers primarily utilized simpler virtual representations, such as paper-based photos and screen-based simulations. A significant transition occurred around 2018, with the advancement of more immersive technologies, including virtual reality (VR) and digital projections. VR technology has become particularly dominant in the 2021–2023 period, where this technology has become both very accessible and offering more and more impressive capabilities.

Despite the growing preference for virtual settings, physical environments continue to be utilized throughout the studied period, underscoring their sustained relevance in biophilic research. The choice between physical and virtual environments often depends on the specific experimental stimuli and the complexity of the study design. Different types of stimuli may be more effectively presented or controlled in either physical or virtual settings. Section 8 will give more insight about which types of stimuli are more suitable for physical environments and which are better suited for virtual settings.

3.1.4. Setups & sample size

The bubble plot in Fig. 5 provides an overview of the experimental setups in all the studies. This visualization helps to fully understand the experiments in the reviewed papers, where the size of each bubble reflects the number of *participants* involved. The color of the bubbles indicates the experimental design type: blue for within-subject designs, green for between-subject designs, and gray for a combination of both. If a paper includes multiple experiments, some conducted under virtual and others under physical conditions, they are presented separately in both plots and are recognizable by their fainter colors.

Most of the studies discussed in this review consider between 2 and 4 independent variables, although some explore up to 36 variables. The shift towards virtual environments for experiments allowed to go way beyond the limit of 10 variables observed for physical settings and emphasizes the practical benefits of virtual settings in making more complex or variable-rich experiments still manageable. However, it also comes with a restriction of the duration of the experiment. While for physical settings, it spans from 25 min to 6 h, with longer durations associated to within-subject designs, it does not exceed 2.5 h in virtual settings which can become uncomfortable after a while. Participant numbers vary significantly, from 15 to 413, with larger groups often linked to between-subject designs in physical environments (and mixed in virtual settings).

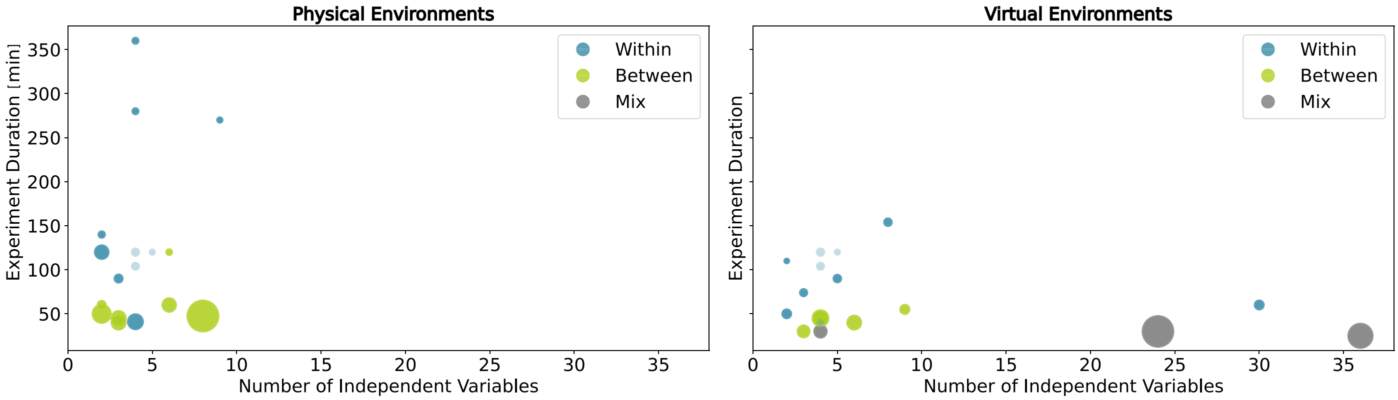

Fig. 5. Distribution of experiment setups and sample sizes, where bubble size reflects the number of participants and color indicates the experimental design; fainter bubbles represent studies involving both physical and virtual settings.

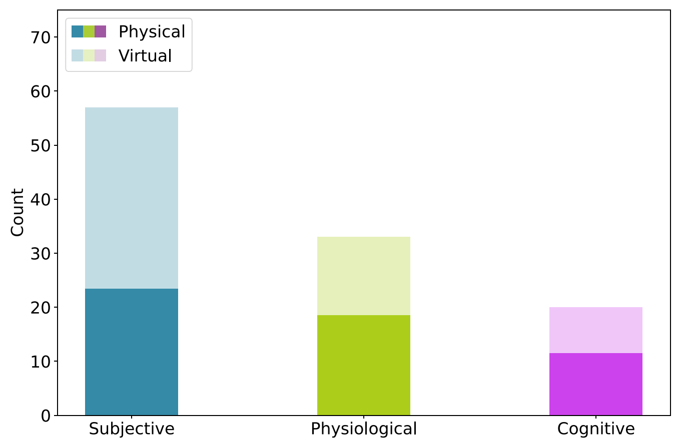

Fig. 6. Types of outcome measures with an indication of the experimental setting (physical vs. virtual).

3.2. Overview of well-being measures

Fig. 6 presents an overview of well-being measures used to assess biophilic environments' influence. These measures can be grouped into three types: subjective, physiological, and cognitive. Subjective measures, involving self-reported data on psychological states and perceptions, appeared in 59 studies, making them the most commonly used. Physiological measures, including objective indicators such as heart rate, blood pressure, and electrodermal reactivity, were used in 34 studies. Cognitive measures, which assess mental processes such as memory, attention, and creativity, were used least in 21 studies.

A detailed analysis of specific well-being measures in each category is presented in Sections 4, 5, and 6, accompanied by Table 3, 4 and Figs. 7, 8, and 9 respectively. The plots provide a breakdown of the data, with significant measures shown in high saturation and non-significant measures shown in low saturation. Counts are grouped into three stimuli: views (orange), shading and light patterns (yellow), and interior design elements (brown). This organization highlights measures that frequently yielded significant results, those that less often demonstrated significance, and those requiring further research despite showing a high proportion of significant outcomes.

4. Subjective measures

Subjective measures, commonly obtained through questionnaires, are widely used in biophilic research. These measures encompass a wide range of elements, including *psychological states*, such as stress, excitement, and relaxation, and *perceptual responses*, such as naturalness and brightness. Fig. 7 presents the subjective measures that have appeared in at least three reviewed studies, divided into these two main groups. Within each group, the measures are ordered from left to right based on the total number of studies that have investigated them. The following analysis highlights consistent trends and notable inconsistencies to clarify each measure's strengths and limitations.

4.1. Psychological states

Psychological states represent internal, subjective experiences reflecting an individual's current mental and emotional condition (Diener & Ryan, 2009). These states are characterized by their experiential nature – they are felt rather than evaluated – and focus on the individual's internal experience rather than environmental features (Larsen & Fredrickson, 1999). In biophilic design research, psychological states serve as indicators of how environmental features influence internal well-being through affective and emotional pathways (Dienes, 2004; Faustino et al., 2021).

4.1.1. Most commonly used psychological state measures

For some psychological states, the proportion of significant effects is low despite a large number of use cases. For example, Perceived *"Stress"* is the most frequently examined state, yet results are often split between significant and non-significant outcomes, making conclusions inconsistent. *"Comfort"* likewise shows mixed findings, suggesting self-reported comfort does not consistently respond to biophilic stimuli. These inconsistencies highlight the need for complementary objective measures – such as physiological indicators of stress (see Section 5) or environmental parameters for comfort – to provide a more complete understanding.

Among the other frequently used subjective measures in psychological research, *"Calmness" and "Pleasantness"* exhibit a higher proportion of significant findings. Natural light and shading patterns inspired by nature – such as sunlight filtered through leaves or reed-like motifs – consistently enhance calmness (Chamilothori, et al., 2022; Chamilothori et al., 2022c; Kong et al., 2022), aligning with findings that fractal patterns have a more calming effect than rigid geometric ones (Abboushi et al., 2019). These soothing effects may occur because such patterns mimic the irregular yet ordered structures of nature to which humans are thought to be evolutionarily attuned (Orians, 2021). Other biophilic elements, like indoor plants and nature-themed decor, have also been shown to increase calmness in occupants (Shibata & Suzuki, 2004). Overall, introducing organic forms and greenery tends to calm the occupants.

"Pleasantness" consistently shows significant responses to biophilic stimuli, though results depend critically on comparison conditions

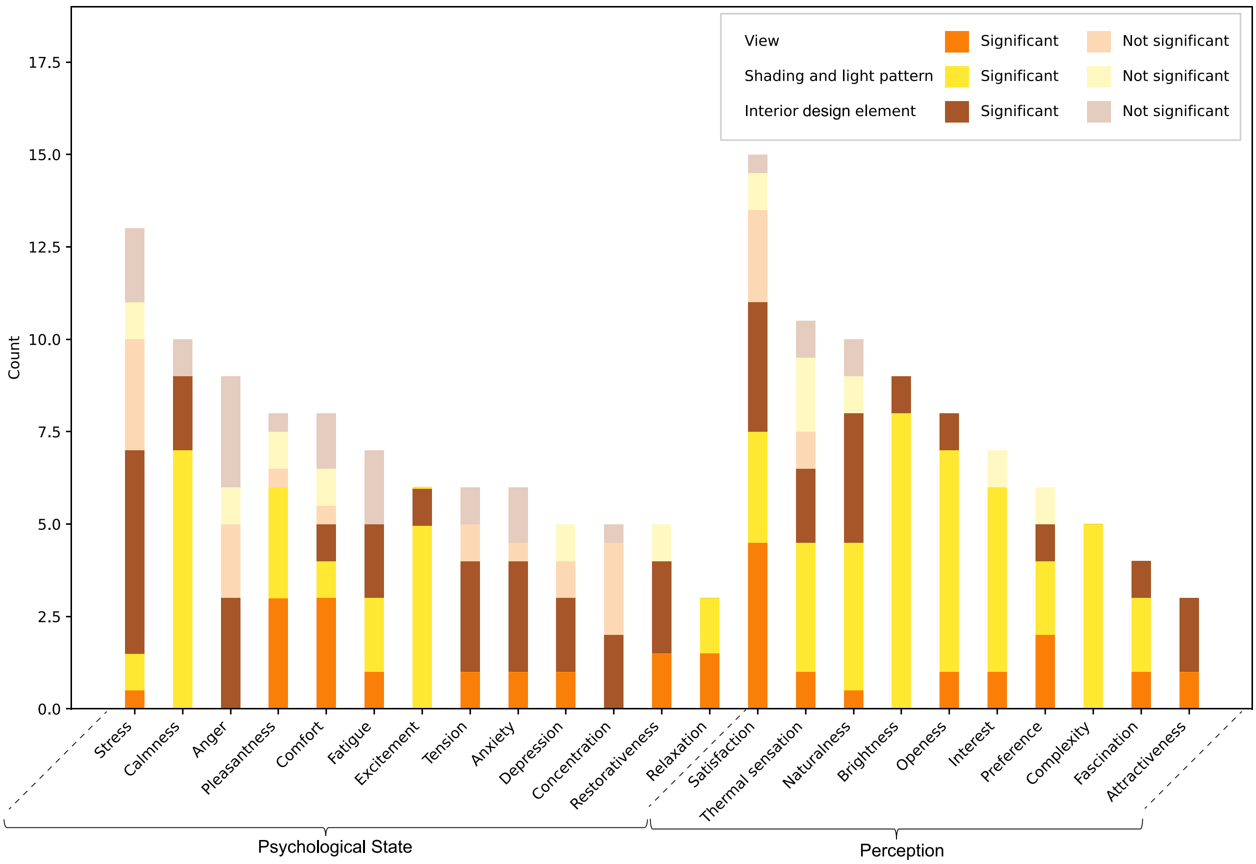

Fig. 7. Subjective measures chosen in the reviewed studies to evaluate different biophilic stimuli with and without significant results.

and environmental context. Studies demonstrate that natural reed-like shading patterns enhance pleasantness (Chamilothori, et al., 2022; Chamilothori et al., 2022c), while irregular square patterns yield contradictory results depending on their comparative baseline (Chamilothori et al., 2019), highlighting how the comparator condition influences outcomes. Similarly, real window views significantly boost pleasantness over blinds or windowless conditions (Ko et al., 2020; Mihara et al., 2022), with plants providing additional enhancement (Elbertse & Steenbekkers, 2023), whereas artificial views in suboptimal settings (e.g., sub-basements) show no effect (Kim et al., 2018). These findings underscore that pleasantness responses are mediated by both stimulus authenticity and environmental quality. Notably, "Calmness" and "Pleasantness" are often linked, with biophilic elements such as shading patterns, window views, and interior design elements like plants capable of enhancing both states simultaneously by contributing to improved feelings of both calmness and pleasantness (Elbertse & Steenbekkers, 2023; Kim et al., 2018).

Less commonly studied emotional states (e.g., *"Fatigue", "Excitement", "Tension", "Anxiety", "Depression", "Restorativeness"*) have been investigated in only a few experiments. Notably, measures like "Excitement" and "Relaxation" demonstrated significant results across all occurrences in biophilic settings. But overall these measures were not used widely enough to draw firm conclusions. They remain potential candidates for further exploration in biophilic design research.

Key points from this section:

- The mixed results for the subjective measure of "Stress" and "Comfort" suggest that it is difficult to draw consistent conclusions about its relationship with biophilic environments.
- Fractal patterns and biophilic elements, like plants, enhance calmness.
- Pleasantness is shaped by window views and plants, influenced by baseline environmental quality and view authenticity.
- Biophilic elements, such as shading patterns, window views, and plants, can enhance both calmness and pleasantness.

4.2. Perceptual responses

Perceptual responses refer to subjective evaluations and interpretations of environmental qualities, representing how individuals perceive and judge their surroundings (Gibson, 1979; Kaplan & Kaplan, 1989). Unlike psychological states that focus inward, perceptual responses maintain direct reference to environmental characteristics rather than personal feelings (Ittelson, 1973; Ulrich, 1983). These responses reflect judgments about what the environment is like rather than how one feels within it.

"Naturalness" and "Openness" are particularly responsive to biophilic design interventions. Sunlight patterns filtering through leaves (known as komorebi) have been found to make environments feel more natural and open (Fujisawa et al., 2012; Ikeda & Oi, 2021; Takayama et al., 2012). Rooms with wood finishes (covering either 45% or 90% of surfaces) were perceived as more natural than those without Tsunetsugu et al. (2007), suggesting wood's potential to enhance naturalness perception when exceeding a minimal threshold. Notably, even in a sub-basement office setting, indoor plants significantly increased perceived naturalness (Kim et al., 2018), though they showed no comparable effect on pleasantness. By contrast, *"satisfaction"* appears most frequently in reviewed studies with significant results, but requires specific contextualization (e.g., with environment, view, or job (Aristizabal, 2021; Du, 2022; Ko et al., 2023)). The limited cases for each satisfaction type prevent definitive conclusions about specific aspects. Taken together, incorporating natural materials, greenery, and dynamic natural light increases how natural and open a space feels.

"Thermal sensation" and "Brightness" perceptions are often studied together due to their shared sensitivity to shading and light patterns,

particularly dappled light effects. However, findings in these domains reveal complex and sometimes conflicting results due to multiple influencing factors. The presence of window views can influence thermal sensations: identical rooms were rated as noticeably cooler with a window view of greenery compared to no view (Ko et al., 2020), while urban views produced no such cooling effect (Mihara et al., 2022). Additionally, material properties play a role, as rooms with wood interiors have been rated as warmer and brighter than non-wood rooms under identical conditions (Zhang, 2016). Beyond these direct effects of natural elements, comparison conditions can significantly alter perceptions: dappled sunlight under a tree canopy was perceived as cooler than full direct sun (Ikeda & Oi, 2021), yet the same dappled pattern appeared warmer when compared to full shade (Fujisawa et al., 2012; Tada & Fujii, 2006; Takayama et al., 2012). These studies suggest that thermal and brightness perceptions are influenced not only by biophilic stimuli – such as natural views and materials, which generally enhance comfort – but also by the comparison conditions, which can shift how the same physical environment is perceived.

Less commonly used measures such as *"Interest", "Preference", "Complexity", "Fascination", and "Attractiveness"* showed a high proportion of significant results, suggesting their potential for further exploration in biophilic design research.

Key points from this section:

- "Naturalness" and "Openness" are closely linked and often show significant responses to shading and light patterns, particularly dappled light under trees (Komorebi).
- Both wood finishes and indoor plants significantly enhance the perception of naturalness, with plants demonstrating this effect even in less favorable environments like sub-basement offices.
- Windows views, especially those including trees, significantly enhance the perception of a cooler temperature.
- Contradictions in thermal and brightness perceptions may arise from comparing dappled light to full shadow or direct sunlight.

5. Physiological measures

Physiological measures are used less frequently than subjective measures, but they provide objective insights into how biophilic environments affect the body. Fig. 8 displays their utilization across studies, grouped by outcomes assessing "Stress", "Visual attention", and "Relaxation". Collecting physiological data often requires specialized equipment or procedures, which can make such measures more challenging to implement. Table 3 summarizes the physiological measures, their descriptions, and measurement procedures, serving as a starting point for evaluating the suitability of each device in research contexts.

5.1. Stress

As Ulrich proposed in his Stress Recovery Theory (SRT) (Ulrich et al., 1991), exposure to nature leads to physiological changes that contribute to stress recovery. This concept is aligned with the fact that the reviewed articles extensively use physiological measures to assess stress levels in biophilic environments.

Each physiological stress indicator has its strengths and limitations: Electrodermal Activity (EDA) captures sweat-based arousal but cannot distinguish stress from excitement; Heart Rate (HR) tends to rise (and Heart Rate Variability (HRV) fall) under stress, though fitness and age also affect these measures; and Blood Pressure (BP) usually increases with stress, though it can be influenced by external factors. Less common measures (skin temperature, Blood Volume Pulse (BVP), salivary cortisol) also respond to stress but require careful control of confounding variables. This section will represent the specifics of each physiological measure and their responses to biophilic stimuli as observed in the reviewed studies.

5.1.1. Electrodermal activity

Electrodermal Activity (EDA) is the most frequently used physiological metric in biophilic research. Several studies report significant EDA changes due to biophilic interior design elements and views, though results vary between physical and virtual reality (VR) environments. For instance, study (Yin et al., 2018) found indoor greenery and window views significantly reduced Skin Conductance Level (SCL), indicating lower stress. Similarly, Kim et al. (2018) observed an even greater SCL reduction when indoor plants were combined with window views, suggesting artificial views may enhance greenery's stress-reducing effects. Moreover, Aristizabal (2021) demonstrated significant reductions in nonspecific skin conductance responses (NS-SCRs) from indoor plants paired with biophilic sensory stimuli. However, several VR studies found no statistically significant SCL reductions despite similar biophilic elements (Yin et al., 2019, 2020), possibly due to altered perception in VR environments.

Research on green walls highlights that wall scale is crucial for effectiveness. Yeom (2021) reported lower SCL with a small green wall compared to a full wall. Similarly, Li (2022) found the greatest SCL reduction with a partially covered green wall. Another experiment showed increasing panel numbers reduced SCL, though not significantly. These variations might result from participants feeling overwhelmed by large-scale vegetation (Yeom, 2021). Further research is necessary to determine optimal green wall size for stress reduction.

Studies exploring natural materials like wood report inconsistent EDA results. Wood furniture reduced EDA in one study (Douglas et al., 2022). However, another study found increased SCL in wooden rooms (Zhang et al., 2017), which the authors attributed to relaxation effects - a surprising finding that contradicts typical EDA interpretations where higher SCL indicates stress rather than calm. Further study is needed to resolve these inconsistencies.

The impact of biophilic shading and light patterns on EDA is mixed, likely due to variations in sample sizes and statistical methods. Chamilothori et al. (2022c) found shading patterns approached significance in $\log \Delta$ SCL with 256 participants using a robust Linear Mixed Model. Conversely, an earlier study (Chamilothori et al., 2019), using simpler ANOVA analysis with 72 participants, found no significant effects, likely due to limited statistical power.

Key points from this section:

- Significant reductions in EDA have been observed in physical environments with biophilic interior design elements and views, while similar studies in VR settings have shown less consistent results, possibly due to the immersive nature of VR affecting the perception of biophilic stimuli.
- Green wall effectiveness depends on scale, with partial coverage reducing SCL more significantly than full coverage, suggesting potential overwhelming effects at larger scales.
- Mixed findings in shading pattern studies highlight how methodological factors like sample size and statistical approaches significantly impact EDA results in biophilic research.

5.1.2. Heart rate and heart rate variability

Heart Rate (HR) and Heart Rate Variability (HRV) are widely used physiological indicators in biophilic research, though findings are often inconsistent. This section explores patterns of variability in these measures, with one key source of variability attributed to confounders such as prior stress exposure and intra-individual differences, including baseline fitness levels.

The role of stress induction emerges as a critical factor in determining the magnitude of HR and HRV responses to biophilic interventions. For instance, Li (2022) found a significant increase in the standard deviation of normal-to-normal intervals (SDNN) and a decrease in HR in response to a green wall—effects that were also reflected in reduced skin conductance levels (SCL). In contrast, other studies (Choi, 2016; Lei et al., 2021; Qin et al., 2014; Yeom, 2021) using similar

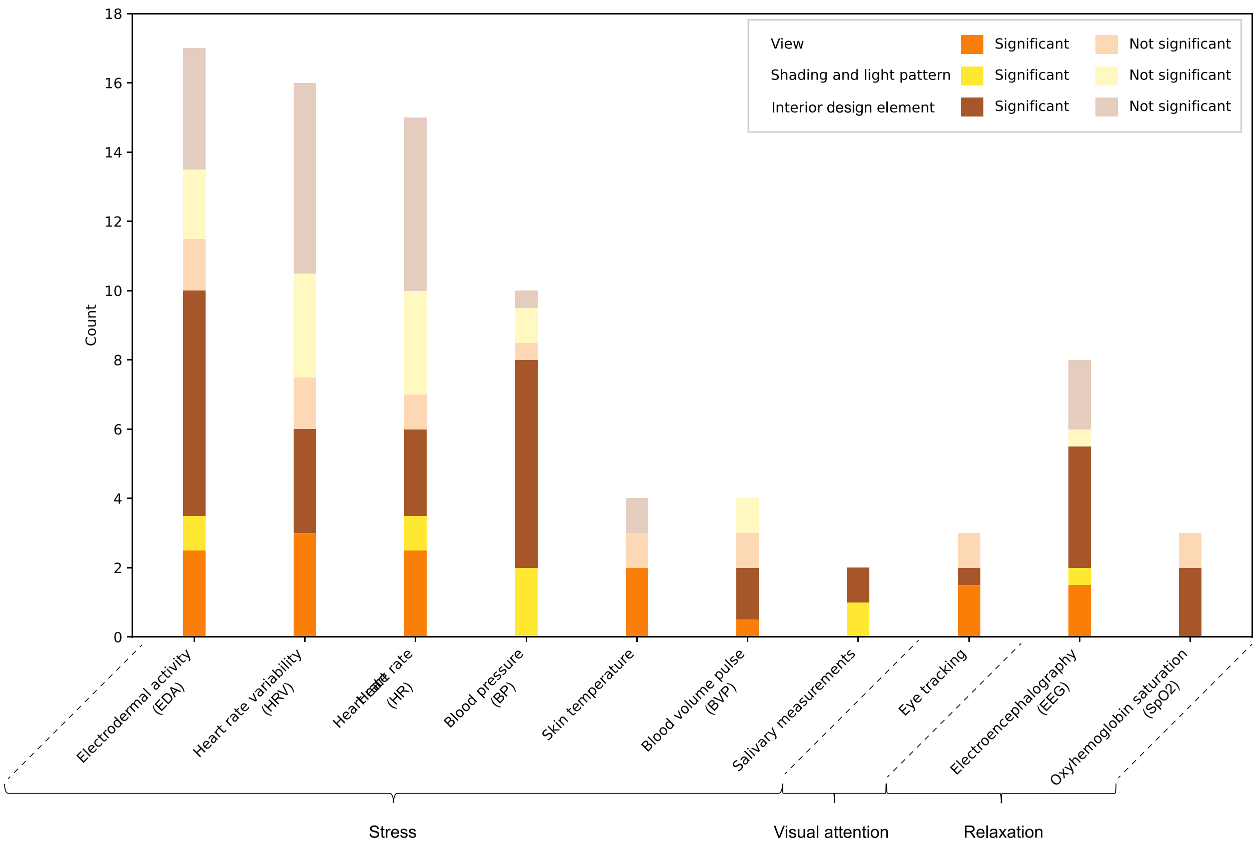

Fig. 8. Physiological measures chosen in the reviewed studies to evaluate different biophilic stimuli with and without significant results.

Table 3
Description and Measurement Procedure of Physiological Measures.

Physiological Measure	Description	Measurement Procedure
Electrodermal Activity (EDA) (Boucsein, 2012)	Measures the electrical conductance of the skin, which varies with its moisture level	Sensors are placed on fingers, wrists, palms, or feet
Heart Rate Variability (HRV) (Guyton & Hall, 2016)	Measures the variation in time between heartbeats, controlled by the autonomic nervous system	ECG or PPG sensors are used in wearables such as chest straps or wristbands
Blood Pressure (BP) (Munakata, 2018)	Measures the pressure of blood in the circulatory system	Cuff-based monitor is placed around the arm
Skin Temperature (Meehan et al., 2002)	Measures the temperature of the skin	Temperature sensors are placed in different parts of the body
Blood Volume Pulse (BVP) (Gouizi et al., 2011)	Measures changes in blood volume in the microvascular bed of tissue	Photoplethysmography (PPG) sensors are used in forms of smartwatch, finger clip, ear clip, or chest straps
Salivary Measurements (Hellhammer et al., 2009)	Measures biomarkers in saliva, such as cortisol levels	Sample collection is required for laboratory analysis
Heart Rate (HR) (Guyton & Hall, 2016)	Measures the number of heartbeats per minute	ECG or PPG sensors are used in wearables such as chest straps or wristbands
Eye Tracking (Rosch & Vogel-Walcutt, 2013)	Captures eye movements and gaze locations	Specialized glasses or a camera mounted on a headset are used
Electroencephalography (EEG) (Soufineyestani et al., 2020)	Measures electrical activity in the brain	Electrodes are attached to the scalp surface
Oxyhemoglobin Saturation (SpO2) (Wukitsch et al., 1988)	Measures the percentage of oxygen-saturated hemoglobin in the blood	Fingertip pulse oximeters are used

greenery-based stimuli reported no significant changes in HRV, including root mean square of successive differences (RMSSD), SDNN, very low frequency (VLF), low frequency (LF), and the low-frequency to high-frequency (LF/HF) ratio, nor in HR. A key difference in Li (2022) was the inclusion of a negative emotion induction phase involving emotion-inducing videos before stimulus exposure, which likely heightened participants' sensitivity and produced more pronounced physiological responses.

This pattern is further supported by studies examining combined biophilic elements. For instance, McSweeney et al. (2021) observed an increase in average intervals between sinus beats (AVNN), but no significant changes in high-frequency power (HF) or in the LF/HF ratio, in environments featuring both windows and plants. Similarly, Yin et al. (2019) found non-significant increases in RMSSD under natural conditions, indicating stress relief. In contrast, Yin et al. (2020), which included a stress induction period, showed significant RMSSD increases during recovery in biophilic compared to non-biophilic environments. Stress induction amplifies HRV recovery effects when exposed to biophilic stimuli, critically enhancing the biophilic impact on HRV, which aligns with findings by Li (2022)

HRV responses to biophilic views vary between VR and physical environments. Mihara et al. (2022) reported elevated RMSSD and the percentage of successive normal-to-normal intervals that differ by more than 50 ms (pNN50) in a VR view condition compared to closed blinds, an effect absent in physical environments. Interestingly, HRV values were similar between VR and physical view conditions but significantly lower in VR with closed blinds. This suggests increased stress in VR environments without biophilic views, intensifying HRV differences.

The subtle effects of Komorebi patterns and plants on HRV and HR have been explored in multiple studies. Karibe et al. (2019) reported reduced HR and higher LF/HF ratios in presence of Komorebi patterns and plants versus a blank wall, though not statistically significant. Similarly, Chamilothori et al. (2022c) found no significant differences in RMSSD in response to shading patterns. Additional studies examining greenery's impact on HR also reported subtle effects: Elbertse and Steenbekkers (2023) showed no significant differences between varying plant conditions near windows; studies (Qin et al., 2014) and Aristizabal (2021) produced comparable non-significant results. These outcomes suggest Komorebi patterns and plants exert subtle influences requiring more sensitive detection methods.

Further, the impact of light patterns on HR depends on comparison conditions. Chamilothori et al. (2019) found significant HR reduction when comparing irregular shading patterns against solid blinds, whereas Chamilothori et al. (2022c) found no significant difference comparing multiple shading patterns. The differing comparison conditions likely resulted in the differences in the experimental results.

The combination of views and biophilic elements, such as plants and wood finishes, notably reduces HR, particularly when multiple elements are combined. Wood finishes significantly decreased HR compared to non-wood alternatives (Zhang et al., 2017). Similarly, Yin et al. (2019) reported significant HR reduction when plants, wood interiors, and views were combined, compared to control. Yin et al. (2020) further supported this, showing the greatest HR reduction with a combined window view and greenery, followed by window-only conditions, though not statistically significant. Studies (Kahn et al., 2008; Mihara et al., 2022) also emphasized the importance of real window views over artificial displays for HR reduction. Thus, combining views and biophilic elements, especially with real window views, enhances HR reduction more than greenery alone.

Compared to HR, HRV demonstrates a greater portion of variability in effectiveness, largely due to the variety of metrics used across the reviewed studies. Some experiments reported time-domain measures of HRV, while others focused on frequency-domain indices. This methodological heterogeneity in HRV computation significantly impacts cross-study comparability, as different indices reflect distinct aspects of autonomic nervous system function and show varying sensitivities to biophilic interventions.

Key points from this section:

- A significant increase in HRV and a significant decrease in HR were observed in one green wall study, but other studies did not find significant changes in either measure, possibly due to differences in emotional induction protocols.
- Elevated HRV values and reduced HR were found with window views, particularly in virtual reality environments. However, these effects were less pronounced in physical settings, likely due to higher stress levels in VR conditions with closed blinds.
- The effects of shading and light patterns on HRV and HR were subtle.
- Heart rate reduction is strongest when combining views with biophilic elements like plants and wood.
- HRV outcomes show high variability, influenced by metric choice.

5.2. Blood pressure

Blood Pressure (BP), less frequently used than EDA, HRV, and HR, consistently demonstrates significant reductions in response to biophilic stimuli. Indoor greenery significantly lowered BP (Yin et al., 2018), as did natural material finishes (Sakuragawa et al., 2008, 2005; Tsunetsugu et al., 2007; Zhang et al., 2017), and their combinations (Yin et al., 2019). Shading and tree-light patterns also significantly reduced BP (Fujisawa et al., 2012; Tada & Fujii, 2006), suggesting BP as a reliable stress reduction measure linked to biophilic elements.

Typically, BP measurements occur before and after exposure using a sphygmomanometer, like the Omron EVOLV monitor. However, some studies (Sakuragawa et al., 2008, 2005; Zhang et al., 2017) employed continuous BP measurement via the Finapres method (Boehmer, 1987). Despite its continuous nature, Finapres might be less accurate than a sphygmomanometer, particularly in specific contexts such as obstetric anesthesia (Epstein et al., 1989).

5.3. Electroencephalography and relaxation

Electroencephalography (EEG) has been widely used to examine how biophilic stimuli affect relaxation. This section explores the influence of green walls, natural shading, and window views on brain activity measured by EEG. EEG records the brain's electrical activity through scalp electrodes, capturing brain waves across frequency bands such as delta, theta, alpha, beta, and gamma. An increase in the values of the alpha band is associated with relaxation and is often used as an indicator of stress reduction (Rosenbaum et al., 2018).

The scale of green walls plays a notable role in EEG responses. Studies found that small green walls produced significantly higher alpha power than large ones (Lei et al., 2021; Yeom, 2021), while another study did not observe significant EEG changes with variation in the density of green walls (Choi, 2016). These results suggest wall size may be more influential than density in promoting relaxation.

Natural elements like shading patterns and window views also show potential in enhancing relaxation. Natural leaf shading significantly increased alpha power compared to artificial materials (Tada & Fujii, 2006). Similarly, participants exposed to window views exhibited higher alpha power than those with closed blinds (Mihara et al., 2022). These findings emphasize the possible role of shading and views in promoting relaxation via increased alpha activity.

Key points from this section:

- Small green walls elicited higher EEG alpha power than large ones, suggesting size affects relaxation, while another study found no impact of green wall density.
- Natural leaf shading and window views have both been shown to significantly increase alpha power, underscoring the potential of natural elements, such as shading and views, to enhance relaxation.

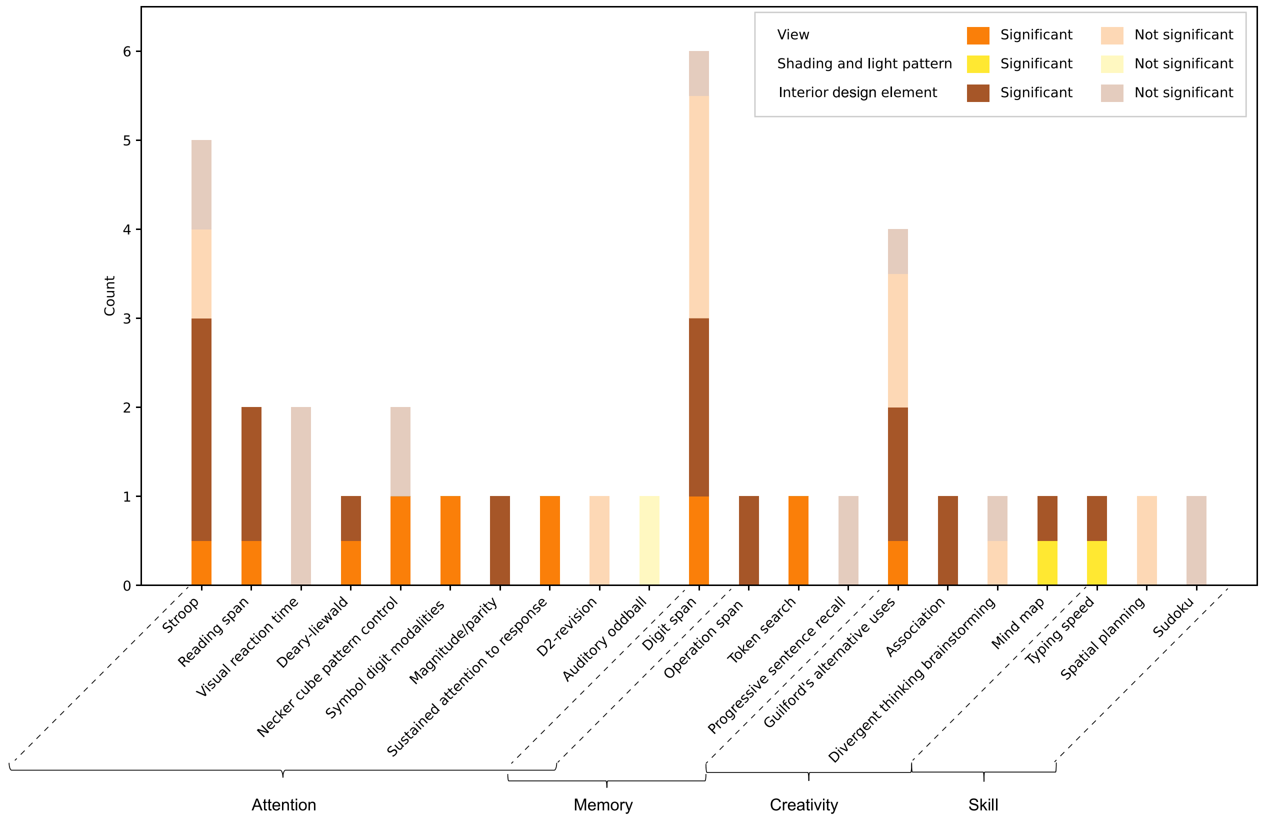

Fig. 9. Cognitive measures chosen in the reviewed studies to evaluate different biophilic stimuli with and without significant results.

6. Cognitive measures

Cognitive measures, assessed through cognitive tasks, have been selectively used in reviewed studies. Fig. 9 illustrates these measures grouped primarily by “Attention”, “Memory”, “Creativity”, or “Skill” with some overlap between categories. For example, the Digit Span and Reading Span tests evaluate both attention and working memory.

Measures related to “Attention” and “Memory” are more frequently used compared to “Creativity”, or “Skill”. Among the specific tests, the *Stroop* and *Digit Span* tests are most common. Cognitive tests typically require more time and mental effort than physiological or subjective measures, influencing their less frequent usage. Table 4 provides detailed descriptions and typical durations of these cognitive tests from reviewed studies.

Interior design elements have shown the most frequent significant impacts on cognitive measures, followed by views, whereas shading and light patterns – often tested in VR – are the least studied in this context, likely because of the added cognitive load imposed by virtual environments. The following sections discuss cognitive measures that frequently yield significant findings.

6.1. Attention

Attention is crucial for cognitive performance and is often assessed through tests measuring focus and processing speed. The *Stroop test* is frequently used, evaluating participants’ abilities to manage competing stimuli. However, results under biophilic conditions vary, with some studies showing reduced reaction times and others reporting increased reaction times. These inconsistencies likely result from variations in experimental protocols. Studies such as Lei et al. (2021) and Aristizabal (2021) reported reduced reaction times with biophilic elements like plants and natural auditory stimuli. Conversely, increased reaction times were observed in studies with repeated Stroop sessions, possibly due to fatigue (Mihara et al., 2022; Yin et al., 2019, 2018).

In contrast, the less frequently used *Reading Span Test* consistently shows significant results. This test evaluates attention and working memory via dual-task activities. Studies indicate that environmental enrichment, such as plants or interior deign objects, combined with window views, significantly enhances performance compared to window views alone (Evensen et al., 2015; Raanaas, 2011). It can be inferred that the view alone does not have a significant impact on the Reading Span Test results, but may even become a source of distraction. However, the combination of view and environment enrichment shows that it enhances the Reading Span Test performance the most.

Key points from this section:

- Stroop test results on biophilic stimuli and attention are mixed, with some showing reduced reaction times and others increased, possibly due to fatigue from repeated sessions.
- A window view alone leads to poor Reading Span Test results, while combining it with environmental enrichment improves outcomes.

6.2. Memory

Memory measures provide insights into an individual’s ability to store and recall information. The *Digit Span Test*, as the second most frequently used assessment in cognitive performance, holds a unique position because it evaluates both short-term memory and attention, depending on how the test is interpreted. While the test requires participants to temporarily store information, it also demands sustained focus, making it a dual measure of cognitive function.

The results of the *Digit Span Tests* in studies focusing on views have been inconsistent, though they generally trend in the same direction, with certain aspects of the view potentially influencing the outcomes. Some studies, such as Li (2016) and Mihara et al. (2022), reported significant improvements in performance with window views compared to no-view conditions, while others, like Tennessen and Cimprich (1995)

Table 4
Description and Test Duration of Cognitive Measures.

Cognitive Measure	Description	Test Duration (min)
Stroop Test (Beute & Kort, 2014; Stroop, 1935)	Name the ink color of a word that is different from the word itself	3
Reading Span Test (Daneman & Carpenter, 1980)	Process and recall sentences while retaining the final word of each sentence	10
Deary–Liewald Test (Deary et al., 2011)	Identifies and marks specific symbols quickly among rapidly presented visuals	5–10
Necker Cube Pattern Control Test (James, 1983)	Control perception between different orientations of a Necker cube	5
Symbol Digit Modalities Test (Smith, 1973)	Substitute numbers for geometric symbols according to a key	1.5
Magnitude/ Parity Test (Arrington & Logan, 2005; Dehaene et al., 1993)	Classify numbers by task type based on color	5
Sustained Attention to Response Test (Robertson et al., 1997)	Holds back responses to rare targets while frequently responding to regular ones	5
Digit Span Test (Leung et al., 2011; Wechsler, 1981)	Recalls sequences of numbers forward and backward	3
Operation Span Test (Foster et al., 2015; Unsworth et al., 2005)	Remember a word while simultaneously solve arithmetic problems	20–25
Token Search Test (Collins et al., 1998)	Recall and manipulate token positions in a grid based on changing instructions	Until 3 errors
Guilford's Alternative Uses Test (Guilford, 1967)	Generates as many uses as possible for a given common object	3
Association Task (Shibata & Suzuki, 2002)	Identifies and names associations for a given word	10
Mind Map Test (Ayuso Sanchez et al., 2018)	Creates a visual diagram of thoughts and ideas around a central concept	15
Typing Speed Test (Ayuso Sanchez et al., 2018)	Measures the number of words typed accurately in a fixed amount of time	15

and Ko et al. (2020), found only slight, non-significant enhancements. Sample size likely is not a factor for this case, as non-significant studies had larger samples. It is possible that differences in view content, with more natural or open views leading to greater improvements, may explain the variability in the results.

It is important to note that the impact of physical versus virtual environments on Digit Span performance appears to depend on the strength of contrast between baseline and biophilic scenes. Yin et al. (2018) and Mihara et al. (2022) reported significant improvements in Digit Span performance in physical biophilic environments (e.g., those with window views or indoor plants), but found no significant effects in their virtual counterparts. In contrast, Mostajeran et al. (2023) observed significant cognitive benefits in a virtual environment when comparing scenes with greenery to those without, suggesting that a pronounced difference between virtual conditions can enhance performance. Notably, all of these studies employed within-subject designs with randomized exposure order, indicating that the observed inconsistencies are unlikely due to methodological issues. Instead, they may reflect intrinsic differences in how individuals experience real versus simulated nature. While virtual environments can produce cognitive benefits when the contrast between enriched and minimal scenes is strong, their effectiveness appears more limited when such differences are subtle.

Key points from this section:

- Digit Span Test performance improved with window views, though significance varied, possibly due to differences in view content.
- The Digit Span test results differ between virtual and physical environments: virtual environments benefit from greenery, while physical environments benefit from window views.

6.3. Creativity and skill

Creativity and skill are less frequently studied cognitive functions in biophilic environment and well-being research. For creativity, tests like *Guilford's Creative Use Test* and *association tests* are used, while skill is assessed through tasks like *typing speed tests* and *Sudoku*. The results in this area are mixed, with roughly half of the studies showing significant effects and the other half not. As a relatively new area of study, it is not surprising that research on attention and memory is more advanced, as these cognitive functions are more directly related to productivity. However, as interest in biophilic environment and well-being grows, creativity and skill-based tasks may gain more attention in future research, though the nature of skill tasks is likely to evolve over time responding to changing demanxds and technologies.

7. Effect sizes

While previously discussed statistical significance (p-value) indicates if an effect exists, effect size quantifies the strength of an effect and is crucial for understanding practical significance (Cohen, 1988). However, only 23% of the reviewed studies reported effect sizes, reflecting that biophilic research is still emerging. This review compiles the reported effect size values (r, η^2, R^2) in Tables 5–7 to inform future studies. The tables also provide details on the stimuli category (Views, Shading and Light Patterns, interior design elements), and the type of outcome measures (Subjective, Physiological, or Cognitive) and the outcome measure actually evaluated.

According to the benchmark suggested by Ferguson (Ferguson, 2009), the effect size can be interpreted as follows: $r < 0.2$, $\eta^2 < 0.04$, $R^2 < 0.04$ are considered negligible; $0.2 \leq r < 0.5$, $0.04 \leq R^2 < 0.25$ and $0.04 \leq \eta^2 < 0.25$ are considered small effect sizes; $0.5 \leq r < 0.8$, $0.25 \leq R^2 < 0.64$ and $0.25 \leq \eta^2 < 0.64$ are considered medium effect sizes, and $r \geq 0.8$, $R^2 \geq 0.64$ and $\eta^2 \geq 0.64$ are considered large effect sizes. Although researchers are cautioned to interpret effect sizes within the specific context of their studies, these benchmarks provide a general guide to understand the magnitude of the effect sizes. The tables below list the effect sizes with color coding based on the benchmarks. For some studies, one outcome measure is associated with multiple test conditions, thus a range of values for effect sizes are reported to reflect the variability of the effect sizes across the different conditions.

Tables 5 and 7 show moderate to large effect sizes for view-related subjective measures. In contrast, non-view-related subjective measures, such as thermal sensation and emotional responses, tend to range from small to moderate. Measures like view access satisfaction (Ko et al., 2023), window view preference (Lin et al., 2022), and satisfaction with outside connection and visual content (Kent, 2020) demonstrate the substantial impact of views. Non-view-related measures, such as thermal and luminous sensation, overall satisfaction, and comfort (Du, 2022), show small to moderate effects. Emotional responses to views, especially high-arousal negative emotions such as fear and hostility (Ko et al., 2020), consistently show small effect sizes. Similarly, studies using η^2 (Douglas et al., 2022; McSweeney et al., 2021; Raanaas et al., 2012; Shin et al., 2022) report small or negligible effects for views on subjective, physiological, or cognitive measures not directly tied to them. These findings suggest that views have the strongest impact when directly linked to satisfaction or preference questions.

Table 6 presents effect sizes of R^2 from studies focusing on subjective measures under shading and light patterns. Effect sizes range from small to medium, varying by stimuli and context. Studies (Chamilothori et al., 2022c) and Chamilothori, et al. (2022), which tested various shading patterns, showed similar small to medium effect sizes, while Moscoso et al. (2021), focusing on window and room size, reported smaller effects. These findings suggest that similar stimuli produce comparable effect sizes, but larger differences in stimuli, such as pattern versus spatial factors, result in varying effects. This supports the idea that effect sizes are context-dependent and must be interpreted within the study's specific framework.

Key points from this section:

- Only 23% of the reviewed studies reported effect sizes, likely due to the exploratory nature of biophilic environment research.
- Moderate to large effect sizes are observed for view-related subjective measures, but effect sizes for other non-view-related subjective measures, such as thermal sensation and emotional responses, tend to be small to moderate
- Effect sizes vary with specific stimuli and study context; similar shading and light patterns yield consistent effects, while differences like shading combined with window size increase variability.

8. Main insights and conclusions

8.1. Bibliophilic stimuli and well-being metrics

The effects of indoor nature on well-being observed in the literature are diverse, but some clear trends emerge. Biophilic features (views of nature, natural light/shadow patterns, indoor plants, and natural materials) consistently enhance occupants' perceptual experience of a space. For example, adding wood textures or dappled light often made spaces feel more "natural" and spacious. By contrast, self-reported stress and comfort showed mixed outcomes, suggesting these emotional state measures are less reliable on their own. In such case, physiological data indicate that biophilic environments tend to reduce stress even when people do not explicitly report feeling less stressed. Indeed, HR was usually lower with a real nature view, and relaxation-related brain activity (alpha waves) increased with natural window scenes or foliage, reinforcing the restorative potential of these elements. In addition, studies also suggest that the dosage of biophilic elements plays a crucial role in their effectiveness—partial green wall coverage often outperformed full coverage for stress reduction, while moderate amounts of wood surfacing proved more beneficial than either minimal or extensive applications. This indicates that a moderate amount of biophilic stimuli, rather than maximizing natural elements, may offer the optimal balance for promoting well-being without overwhelming occupants or diminishing the intended restorative effects. As for cognitive performance, the evidence for cognitive performance benefits from biophilic design is mixed and relatively limited. While some studies demonstrated improvements in attention and memory tasks with nature exposure – particularly when combining window views with indoor plants – others found minimal effects or even distraction from window views alone. Given the small evidence base, conclusions about cognitive benefits remain preliminary, and further research is needed to clarify the relationship between biophilic environments and cognitive function.

Despite these emerging insights, the current research landscape shows notable gaps in coverage. Research has concentrated primarily on views and interior design elements, while shading and light patterns – despite demonstrating clear benefits – remain understudied. Finally, although limited number of studies reported formal effect size statistics, the data compiled in this review suggest that biophilic interventions often have moderate practical effects on subjective well-being (especially for outcomes directly tied to natural view exposure), while physiological and cognitive effects tend to be smaller or more dependent on context. Overall, biophilic design interventions show measurable benefits across subjective, physiological, and cognitive dimensions, although the magnitude and consistency of these benefits vary depending on the type of stimuli and the well-being metrics used.

8.2. Influences of context, baseline, and experimental environment

In addition to the biophilic stimuli, a lot of variability in the effectiveness of biophilic interventions across studies can be explained by the context in which interventions are targeted, the baseline conditions against which they are compared, and whether exposure occurs in physical or virtual experimental environments.

The context of biophilic experiments varies across work, social, and rest environments. The context of biophilic experiments spans work, rest, and social environments, with each setting emphasizing different outcome priorities. In work-focused settings, where task performance and stress regulation are central, studies consistently report measurable improvements in attention, memory, and task-switching abilities, alongside reductions in physiological stress markers such as heart rate variability (HRV), skin conductance, and EEG indicators. Subjective outcomes like job satisfaction, mental fatigue, and perceived restorativeness also show marked improvement in the presence of plants, natural materials, green walls, and outdoor views. In contrast, rest and social environments – including dormitories, hospital waiting rooms, lounges, and cafes – are primarily studied for their restorative effects. Here, cognitive testing is rare, but subjective mood assessments (e.g., POMS, SD scales, VAS) and physiological signals (e.g., reduced blood pressure and arousal) show strong responses to biophilic features such as wood textures, dynamic natural lighting (e.g., komorebi),

Table 5
Effect Sizes with Indices r. For $r < 0.2$, the number is lightgray, for $0.2 \leq r < 0.5$, the number is gray, for $0.5 \leq r < 0.8$, the number is **darkgray**, for $r \geq 0.8$, the number is **black**.

Author	Stimuli	Types of Outcome Measures	Outcome Measures	Effect Size (r)
Ko et al. (2023)	Views	Subjective	View Access Satisfaction	0.13 – 0.83
Lin et al. (2022)	Views	Subjective	Window View Preference	0.5983
Kent (2020)	Views	Subjective	Satisfaction with Connection to Outside	0.6
			Satisfaction with Visual Content	0.68
			Satisfaction with Visual Privacy	0.51
Du (2022)	Views	Subjective	Thermal Sensation	0.049 – 0.094
			Thermal Satisfaction	0.016 – 0.317
			Luminous Sensation	0.056 – 0.191
			Luminous Satisfaction	0.088 – 0.359
			Overall Comfort	0.145
			Overall Satisfaction	0.068
Ko et al. (2020)	Views	Subjective	High-arousal positive (HAP): enthusiastic, excited, elated	0.25
			Positive (P): happy, satisfied, content	0.36
			Low-arousal positive (LAP): calm, relaxed, peaceful	0.23
			Low-arousal (LA): quiet, still, passive	0.17
			Low-arousal negative (LAN): dull, sleepy, drowsy	0.35
			Negative (N): sad, lonely, unhappy	0.32
			High-arousal negative (HAN): fearful, hostile, nervous	0.02
			High-arousal (HA): surprised, astonished, aroused	0.18

Table 6
Effect Sizes with Indices R^2. For $R^2 < 0.04$, the number is lightgray, for $0.04 \leq R^2 < 0.25$, the number is gray, for $0.25 \leq R^2 < 0.64$, the number is **darkgray**, for $R^2 \geq 0.64$, the number is **black**.

Author	Stimuli	Types of Outcome Measures	Outcome Measures	Effect Size (R^2)
Moscoso et al. (2021)	Shading and Light Patterns	Subjective	Pleasantness	0.027
			Calmness	0.044
			Interest	0.132
			Excitement	0.112
			Complexity	0.167
			Satisfaction with the Amount of View	0.066
			Spaciousness	0.243
Chamilothori et al. (2022c)	Shading and Light Patterns	Subjective	Pleasantness	0.38
			Calmness	0.38
			Interest	0.53
			Excitement	0.53
			Complexity	0.56
			Satisfaction with the Amount of View	0.53
			Spaciousness	0.65
			Brightness	0.60
Chamilothori, et al. (2022)	Shading and Light Patterns	Subjective	Pleasantness	0.38
			Calmness	0.37
			Interest	0.52
			Excitement	0.50
			Complexity	0.53
			Satisfaction with the Amount of View	0.54
			Spaciousness	0.60
			Brightness	0.61

and multisensory natural elements. Although these settings have been studied less frequently, existing research finds pronounced gains in relaxation, mood, and psychological restoration when indoor environments incorporate abundant greenery, natural materials, or variable lighting. These restorative effects not only improve well-being in the moment but can also indirectly support subsequent work by facilitating more effective recovery from stress. This reveals a significant opportunity to expand research into rest and social contexts, which may offer substantial restorative potential.

Moreover, the comparator or baseline condition against which a biophilic environment is evaluated plays a critical role in the magnitude of reported benefits. Biophilic interventions tend to show the strongest benefits when the baseline condition lacks natural elements entirely. For example, introducing a window with views of greenery or natural scenery produces significant improvements in thermal comfort perceptions and subjective pleasantness when the alternative is a windowless room or blank wall. However, these similar natural views may show minimal or no measurable benefits when compared to conditions that already provide some positive stimulation, such as urban views. This baseline dependency is also evident across various studies in light patterns. The perception of dappled sunlight (komorebi) illustrates this principle clearly: it feels cooler relative to direct sunlight but warmer when compared to full shade. This baseline dependency is further demonstrated across different studies on shading patterns: in one study,

Table 7
Effect Sizes with Indices η^2. For $\eta^2 < 0.04$ the number is lightgray, for $0.04 \le \eta^2 < 0.25$ the number is gray, for $0.25 \le \eta^2 < 0.64$ the number is **darkgray**, for $\eta^2 \ge 0.64$ the number is **black**.

Author	Stimuli	Types of Outcome Measures	Outcome Measures	Effect Size (η^2)
Raanaas (2011)	interior design elements	Cognitive	Word Memorization	0.01 – 0.06
Lee (2023)	interior design elements	Subjective	Anxiety	0.06
			Perceived Wait Time	0.03
			Comfortable Wait Time	0.03
			Perceived Service Quality	0.06
Shin et al. (2022)	Views	Subjective	ROS	0.136
			PRS	0.088
			PRS Being Away	0.133
			PRS Coherence	0.002
			Fascination	0.12
			Scope	0.04
Raanaas et al. (2012)	Views	Subjective	Mental Health	0.03
			Physical Health	0.01
McSweeney et al. (2021)	Views and interior design elements	Physiological	HRV:AVNN	0.08
			HRV:HF	0
			HRV:LF/HF	0.01
		Subjective	Satisfying-Annoying	0.15
			Clean-Dirty	0.11
			Relaxing-Stress	0.23
			Comfortable-Uncomfortable	0.22
			Colorful-Dull	0.37
			Happy-Sad	0.28
			Bright-Dull	0.09
			Spacious-Crowded	0.1
			Calming-Irritating	0.26
			Warm-Cool	0.09
			Attractive-Unattractive	0.29
			Quiet-Noisy	0
			Pleasant Smell-Unpleasant Smell	0.11
Douglas et al. (2022)	Views and interior design elements	Subjective	Self-Reported Belonging	0.001
			Self-Reported Stress	0.01 – 0.001
			Self-Reported Negative Arousal	0.01 – 0.02
			Self-Reported Positive Arousal	0.01 – 0.001
			Self-Reported Creativity	0.001 - 0.002
			Self-Reported Pro-Environmental Concern	<0.001
			Self-Reported Pro-Environmental Concern	0.001 – 0.003
		Physiological	Physiological Stress	0.001 – 0.01
		Cognitive	Divergent Creativity	0.002 – 0.01
			Convergent Creativity	<0.001

geometric patterns significantly influenced pleasantness when compared to blank controls, while in another study comparing geometric patterns to alternative patterns, no significant differences were found. These findings suggest that the effects of biophilic interventions may be influenced by their comparison conditions. Caution is needed when interpreting results across studies for their comparator conditions.

The experimental environment – whether physical or virtual – also shapes intervention outcomes. Physical exposure to nature consistently produces stronger and more reliable effects than screen-based or virtual reality presentations of identical biophilic elements. When researchers introduced real indoor plants and window views in actual office spaces, participants showed measurable stress reduction through lower skin conductance levels. Yet parallel studies using virtual reality recreations of these same plant-and-view configurations found no comparable physiological improvements. This trend extends to cognitive performance, with physical biophilic environments – featuring window views or tangible plants – enhancing working memory tasks, whereas the virtual settings did not. The inconsistent results in virtual environments, compared to the reliable effects of physical settings, may originate from the inherent tension and cognitive load that VR introduces. However, some VR studies have still demonstrated significant cognitive benefits, suggesting that the magnitude of contrast between intervention and baseline conditions may be a important factor for virtual environments to show effects. Overall, physical environment offers an authenticity advantage through multisensory engagement that virtual environment cannot fully replicate. While virtual environment provides valuable experimental control for testing complex design variations like dynamic lighting patterns, the cognitive load and perceived artificiality inherent in VR must be carefully considered when designing experiments.

8.3. Limitations

There are several limitations to acknowledge in this body of research. This review focused exclusively on visual biophilic stimuli – namely views, shading/light patterns, and interior design elements – due to their prevalence and architectural relevance in existing research. However, this scope excludes other sensory dimensions such as auditory, olfactory, thermal, and tactile cues, which may also contribute meaningfully to human well-being in built environments. In addition, this review intentionally focused on short-term effects assessed through subjective, physiological, and cognitive measures – reflecting the most commonly used approaches in biophilic research – this scope necessarily excludes other outcome domains. Longer-term impacts such as behavioral adaptation, chronic health changes, or neurobiological responses were beyond the review's scope and remain underexplored. We systematically synthesized well-being metrics by stimulus type and outcome significance (significant vs. not), to highlight which combinations of stimuli and measures show the strongest evidence for biophilic impact. However, this binary classification is limited by variability in how studies define significance (e.g., differing p-value thresholds, lack of correction for multiple comparisons) and by publication bias, as studies with non-significant results are less likely to be published, potentially skewing the overall pattern. As a result, these aggregated counts should be interpreted as indicative of research attention and reported effects, rather than as definitive measures of intervention efficacy.

8.4. Outlook

Looking ahead, this review highlights several promising directions for future research. First, there is a clear need for more studies focused on shading and light patterns, as these areas remain underexplored despite their well-documented benefits. Expanding biophilic research beyond workplace settings to include rest and social environments could also provide valuable insights into the broader restorative potential of biophilic design. Additionally, combining both subjective and physiological measures is crucial for a more comprehensive understanding of complex well-being constructs such as "Stress" and "Comfort". Addressing the issue of multiple tests by refining significance thresholds and carefully considering the number of hypotheses tested would enhance the rigor of future studies. Lastly, standardizing the reporting of effect sizes would enhance understanding of practical influence and guide decisions on sample size and study design in future research.

CRediT authorship contribution statement

Zhujing Zhang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marilyne Andersen:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors used AI-assisted technologies solely to improve readability and language. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the final version of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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