Journal of Building Engineering 98 (2024) 111127

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Evaluating Biophilic Design strategies in Immersive Virtual Indoor Environments: A systematic review on the implications for buildings occupants

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ARTICLE INFO

Keywords:
Biophilic design
Virtual reality
Human comfort
Human perception
Human performance
Occupant health and well-being

ABSTRACT

Nowadays, investigating the impact of Biophilic Design (BD) on human health, well-being, and cognitive performance is at the forefront of concern in academia, particularly in the context of creating sustainable and comfortable buildings by fostering a deeper connection to nature. In parallel, the advancement and accessibility of Virtual Reality (VR) have facilitated the rise of immersive studies on BD, offering advantages in terms of flexibility, cost-effectiveness, and control over independent variables. However, despite the body of research is growing, it remains fragmented, with heterogenous design of experiments and methods across studies, particularly concerning the outcomes of BD impact on human dimension. This is due to the novelty of these topics which did not allow the systematical synthetisation of the potential benefits of VR-BD applications. As a result, the present paper addresses the need to consolidate an emerging and under-investigated field, offering a systematic and comprehensive overview of the current literature to advance research application. In particular, the review focuses on the applications, potentials, and constraints of the use of Immersive Virtual Reality to investigate the impact of indoor Biophilic Design on occupants' dimension, in terms of environment perception, physiological and psychological indicators and cognitive functions. Although the first literature dates back to 2015 and most of it is concentrated in the last 5 years, enough information has been gathered to provide a systematic review of the methods used and the main results collected, which can serve as a guideline for future research on this emerging topic. The systematic review, based on the PRISMA method, provides a clear picture of the methodological design of the studies (e.g., VR technology and software employed, participants sample size, exposure time, ecological validity methods), on the considered independent variables (i.e., the BD patterns); and on collected dependent variables, related to perception domains (i.e., acoustic, visual and thermal perception, perceived restoration), physiological parameters, psychological and cognitive aspects. The review then reports and analyses the main outcomes from the research in terms of the impact of indoor biophilic strategies on dependent variables, outlining a rather fragmented picture and only partially supporting the theories of BD. Finally, the review presents the main shortcomings and limitations in the design and documentation of the reviewed studies, as well as potential future

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https://doi.org/10.1016/j.jobe.2024.111127
Received 21 May 2024; Received in revised form 17 October 2024; Accepted 20 October 2024
Available online 21 October 2024

research developments, especially based on the exploitation of advantages of VR technologies in terms of a great number of randomized and multi-domain scenarios to be tested.

Abbreviations			
ART	Attention Restoration Theory	IVE	Immersive Virtual Environment
ASE	Affective and Spatial Experience	MAS	Momentary affective state
BD	Biophilic Design	PANAS	Positive and Negative affect scale
BIDI	Biophilic Interior Design Index	POMS	Profile of Mood States
BP	Blood Pressure	PRS	Perceived Restorativeness Scale
CAVE	Cave Automatic Virtual Environment	ROS	Restorative Outcome Scale
EDA	Electrodermal activity	SAM	Self-assessment manikin questionnaire
EEG	Electroencephalography	SC	Skin Conductance
GUI	Graphical User Interface	ST	Skin Temperature
HIRS	Hospital Indoor Restoration Scale	STAI	State-Trait Anxiety Inventory
HMD	Head Mounted Display	SRT	Stress Reduction Theory
HR	Heart rate	SSQ	Simulator Sickness Questionnaire
HRV	Heart rate variability	VAS	Visual Analogue Scale
IBE	Immersive Biophilic Environment	VR	Virtual Reality
IPQ	Igroup Presence Questionnaire	ZIPERS	Zuckerman Inventory of Personal Reactions

1. Introduction

1.1. Biophilic design: concept, patterns and theories

In contemporary societies, the quality of the indoor environment has emerged as a crucial determinant of overall well-being [1,2]. With the ongoing increase in the average time spent indoors [3,4], understanding and enhancing the indoor environment have become imperative for fostering occupant comfort, work-efficiency, and health.

Biophilic Design (BD) is a conceptual framework rooted in the idea of reconnecting individuals with nature within the indoor environment [5–7]. BD recognizes the inherent human need for a connection with the natural world and seeks to integrate natural structures into indoor spaces. Incorporation of Biophilia into the built environment is possible through a rich diversity of strategies, and for this reason, BD can be organized into three main categories, which include further biophilic design patterns (Table 1), described as follows [8]: **"Nature in the Space"** focuses on the direct and physical presence of nature in space; **"Natural Analogues"** refers to organic, non-living and indirect evocations of nature and encompasses three patterns of biophilic design; "**Nature of the Space"** addresses spatial configurations in nature and encompasses four biophilic design patterns.

Patterns of each category can be individually integrated into the indoor environment or combined to create a diverse range of biophilic design strategies. Nature has been primarily linked to positive effects on individuals through the well-known Attention Restoration Theory (ART) by Kaplan [9,10] and Stress Reduction Theory (SRT) by Ulrich [11]. The ART suggests that spending time in nature or environments with natural elements can restore mental fatigue and improve cognitive function. Natural settings, characterized by elements like greenery, water, and open spaces, promote involuntary attention, allowing individuals to recover from the

Table 1
14 Patterns of Biophilic Design defined by Terrapin Bright Green [8].

Patterns of Biophilic Design	Description
Nature in the Space	
1. Visual Connection	A view to elements of nature
2. Non-Visual Connection	Natural sound, touch, smell or taste stimuli
3. Non-Rhythmic Sensory Stimuli	Stochastic and ephemeral connections with nature
4. Thermal & Airflow Variability	Natural fluctuation in air temperature, relative humidity, airflow
5. Presence of Water	Enhancing a place through seeing, hearing, or touching water
6. Dynamic & Diffuse Light	Light and shadow variations resembling natural conditions
7. Connection with Natural Systems	Awareness of seasonal and temporal natural processes
Natural Analogues	
8. Biomorphic Forms & Patterns	Symbolic references to natural contours, patterns, textures
9. Material Connection	Materials and elements from nature
10. Complexity & Order	Sensory richness that adheres spatial natural hierarchy
Nature of the Space	
11. Prospect	An unobstructed view over a distance
12. Refuge	A place for protection and withdrawal from environmental conditions
13. Mystery	Entice the individual to travel deeper into the environment through partially obscured views or other sensory devices
14. Risk/Peril	An identifiable threat coupled with a reliable safeguard

mental fatigue associated with directed attention. Similarly, the SRT is another concept related to the influence of nature on well-being, particularly in the context of environmental psychology. The theory suggests that natural environments can help reduce stress and lead to a state of physiological and psychological restoration, identifying the natural elements as the responsible activators of our nervous, cardiovascular, and neuroendocrine systems. As a result, those theories have guided biophilic research determining the aspects and benefits for individuals to be investigated as dependent variables within studies (i.e., physiological, psychological, perceptual, cognitive). Also based on these theories, five main literature reviews extensively report BD benefits for occupants [7,12] especially in specific contexts, such as university buildings [13], healthcare facilities [14], and office environments [15].

1.2. Virtual reality for BD research

The above-mentioned research is mainly carried out in "physical" spaces, such as climatic chambers, test or real rooms, and living labs, integrated with natural elements, specific architectural designs or audio reproduction settings. However, this kind of investigation implies the need for expensive changes to the layout of the test environment, especially when multiple biophilic patterns are compared. In other studies, participants are exposed to biophilic environments represented in photos or videos, with the risk that people express a preference for a particular biophilic attribute that does not align with their actual perceptions when immersed in a realistic context.

To overcome these problems, BD research can be conducted in Virtual Reality (VR). VR has the ability to streamline the design process [16] by empowering researchers and professionals to integrate the «human dimension» from the initial design phases, enabling the measurement of end-user behaviour with real-time feedback collection. Numerous studies have showcased the substantial potential of this technology in replicating real-world settings (e.g., Refs. [17–22]), ensuring a heightened level of "ecological validity" (the ability of virtual environments to adequately represent real settings). Indeed, VR technology is a cost-effective and flexible solution enabling the creation of immersive, realistic, and multi-sensory simulated spaces to collect complex data, breaking free from the constraints of laboratory-based studies [19,23–25]. VR experiences in research settings designed for total immersion can be designed and offer an excellent opportunity to study individuals' responses. As a result, VR is emerging as a valid alternative for evaluating built environments due to the ability to easily control selected variables, especially the visual dimension, and analyse cause-effect relationships.

The advantages and potential of VR in supporting building occupant-centric design and research are strongly related to its definition. Indeed, VR has been defined as a technology that uses computers, software, and peripheral hardware to generate a simulated environment for its users allowing them to interact and have a sense of being present in a virtual environment different from the one they are actually [26]. This definition poses that several VR technologies exist which can be categorized by their level of immersion. «Immersion » indicates the «state in which a participant becomes attracted and involved in a virtual space of an activity to an extent that his or her mind is separated from the physical space he or she is being active in» [27,28]. The level of immersion is a multifaceted concept. It strictly depends on technological requirements (i.e., hardware, software [29]), sensory engagement capable of enhancing the users' presence (i.e., sight, sound, touch, smell, taste), psychological sense of being present within the virtual environment, interactivity between the user and the virtual word, realism in terms of fidelity and details of the virtual word, isolation from the surrounding Real Environment [28]. Consequently, the more senses engaged in a realistic way, the higher the virtual environment is perceived as an actual place, the higher the levels of interactivity, the highly detailed and realistic the virtual environments are, the more the virtual devices exclude the Real Environment and replace it entirely with a virtual one, the greater will be the sense of immersion [30–33]. As a result, the following taxonomy that ranges from low to high levels of immersion can be highlighted [26,34]:

- "**Non-Immersive VR Systems**" provide a basic virtual experience with a low level of immersion to users who interact with a 3D environment through a standard computer monitor.
- "**Semi-Immersive VR Systems**" use large screens, such as CAVE (Cave Automatic Virtual Environment) or projection-based systems, to display a virtual environment. The level of immersion is medium because the users have only limited spatial interaction and are not fully included in the virtual environment.
- "**Fully Immersive VR Systems**" provide a very high level of immersion to users through Head-Mounted Displays (HMDs) or VR headsets which completely exclude the real environment and experience a 1:1 scale virtual environment. These systems are integrated with motion tracking and controllers to achieve and enhanced presence and interaction.

Among fully immersive virtual technologies, **Immersive Virtual Environments** (IVEs) provide the highest level of immersion and user interaction. IVEs are extremely versatile. This is especially true considering the easy and effective way of manipulating the visual dimension to create virtual elements and also integrating the acoustical domain.

1.3. Literature gap and review aim

Thanks to VR capacity of immersing users in the virtual environment and isolating them from the outside real world (Real Environment), IVEs have a great potential for conducting biophilic research studies. It is possible to implement several biophilic patterns from both a visual and acoustical point of view by simply leveraging the audiovisual characteristics and elements of IVE devices. That is why, in recent years, the intersection between Biophilic Design, Virtual Reality and the human dimension has become a hot research topic, leading to an increasing number of papers. However, current available investigations appear fragmented in terms of metrics and methods, resulting in a body of knowledge with limited impact on BD practice. This overview pinpoints the need to follow the emerging research flow by reviewing, reporting and systematizing methods, results, potentials and limitations of current literature employing VR to investigate BD strategies, to support researchers in enhancing this multidisciplinary research topic and to further sustain evidence-based practices in indoor building design.

To the best of the authors' knowledge, only 2 literature reviews on the subject exist. The first one [27] is focused on 36 studies from 2006 to 2020, which used VR (non-immersive and immersive) to evaluate the effectiveness of virtual natural environments and settings in various domains. Nevertheless, this review includes only 7 papers addressing the biophilic indoor environment, being mainly focused on the effects of biophilic outdoor environments, urban green spaces, streetscapes, and wild nature. Furthermore, this work is limited in time, considering the high number of works on indoor biophilic design in the last 4 years (as highlighted in Section 3.1). The second one [35] entails research conducted both in real-world and VR settings, in order to assess the effects of exposure to natural environments on physiological outcomes related to stress. Hence it does not address BD indoors.

The present work then strives to address this literature gap, aiming at comprehending the existing knowledge on the applications, potentials, future directions and constraints of immersive VR to support indoor Biophilic Design research on building occupants' dimension. In particular, this review focuses on works where IVEs provide different types of visual or acoustic stimuli related to indoor biophilic patterns experimentally manipulated and controlled by researchers, and where participants subjects immersed in the IVEs perform cognitive tests and subjective evaluations of their perception and emotions. The field of study concerns indoor immersive applications of Biophilic Design (Immersive Biophilic Environments, IBEs) in specific settings, i.e. residences, schools, workplaces and hospitals, where the literature is more widespread, and the application of BD has the greatest potential impact. In addition, only studies adopting fully immersive VR technologies are included in this review, given their higher sense of presence and realism offered to the participants.

In detail, the review objectives are to: a) classify the widespread experimental settings and methods of VR-based literature examining the impact of nature indoor; b) illustrate the main results on the impact of biophilic strategies on cognitive functions, perception of the environment, physiological and psychological wellbeing, in relation to different scenarios investigated in IVEs; c) provide an overview of the literature status also identifying limitations and future research directions within this domain.

The paper is then organized as follows: Section 2 defines the methodology adopted to carry out the literature review, and Section 3 conducts a thorough review of VR applications within the BD domain. In particular, Section 3.1 presents the research trends, Section 3.2 focuses on biophilic patterns investigated and on the experimental design and technologies adopted by the selected studies to carry out experiments, Section 3.3 delves into the different methods used by researchers to collect dependent variables related to the environment perception, the physiological and psychological indicators and the cognitive functions, while Section 3.4 presents the

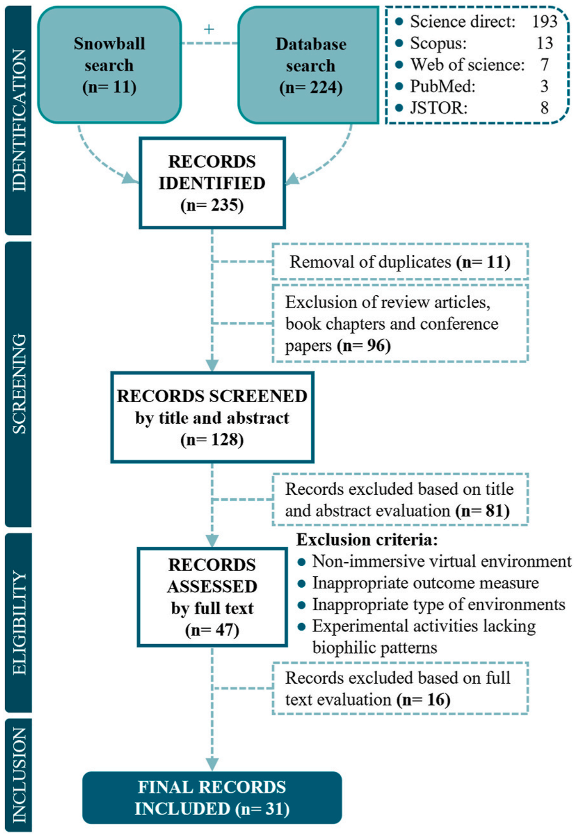

Fig. 1. Flowchart detailing the review research methodology.

outcomes in terms of the BD impacts on the dependent variables demonstrated by the examined literature. Finally, Section 4 presents key observations and discuss future directions for biophilic research using IVEs, and the conclusions are in Section 5.

2. Review method based on PRISMA workflow

The chosen methodology for this study is the systematic review, a widely used and efficient approach that ensures transparency and replicability of the process of reviewing, summarising, evaluating, and communicating existing scientific evidence within a specific subject area [36]. In conducting this review, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was adopted [37,38]. It involved four phases, as explained in the following subsections: (1) identification of records through database searching and other sources; (2) screening of records to select the relevant literature; (3) evaluation of the eligibility of full-text articles based on specific criteria; (4) inclusion of studies in the review. Fig. 1 illustrates the flowchart of the review process.

2.1. Identification and screening steps

As a first step of the review process, a primary search using advanced search features of "Science Direct", "Scopus", "Web of Science", "PubMed", and "JSTOR" databases was conducted in October 2023 and updated in January 2024. "Google Scholar" was excluded due to inconsistent indexing and limited search options, which could affect the reliability of the review [39]. To be included in the present review, articles needed to be exclusively focused on fully immersive Virtual Reality models representing indoor spaces referred to residences, schools, workplaces and hospitals, used to evaluate the impact of Biophilic Design strategies on building occupants. No temporal restriction has been established on publication year, in order to enable comprehensive examination of all relevant studies published in the English language. Thus, three sets of keywords, internally joined by the OR operator and connected with the AND operator, were considered, and reported in full in Table 2:

- The first set included keywords referring to the *use of Virtual Reality* for conducting the experiments. Immersive Virtual Environments were exclusively considered for the present review because they provide the highest level of immersion among virtual technologies. Unlike non-immersive and semi-immersive VR systems, Augmented Reality, and Mixed Reality, which offer varying degrees of immersion from low to medium by enhancing real or combining real and virtual elements, IVE fully immerses users in a 1:1 scaled environment and allows for an effective and easy control of the visual variable, making those environments the most suitable approach for the BD research objectives [19,23].
- The second set concerned the indoor built environments as the *place settings* of the experimental activities, and it was deliberately kept general to avoid excluding studies that solely focus on experimenting generic indoor spaces, such as empty rooms without furniture or objects other than biophilic elements, without mentioning a particular type of building.
- The third set covered the *Patterns* of *Biophilic Design* defined by Terrapin [8] and summarised in Table 1. Words belonging to patterns « Presence of Water», «Connection with Natural Systems», «Refuge, «Mystery and «Risk/Peril» were excluded from the search terms list, as they were not considered relevant to the objective of the review as for indoor space design.

The selected search query returned a total of 224 articles. The review considered 11 additional papers whose identification was not covered by the above-mentioned query and discovered through alternative sources (snowball search). In particular, these were obtained by a backwards and forward search of cited or citing articles, deeming them as potentially relevant despite not being identified through the systematic review process. An additional record (Ref. [40]) was identified by the authors' collective knowledge. Finally, a total of 235 studies were derived during the Identification phase. Throughout the second step of the review process (Screening phase) 11 duplicates and 96 conference proceedings, review articles and book chapters were filtered. This step then allowed the exclusion of 107 documents, leaving 128 research articles for the next phase. Finally, titles and abstracts of the selected articles were then scanned by two authors to address potential bias in the process related to a unilateral decision by a single-author decision, thus excluding 81 articles [41].

Table 2
List of concepts, term combinations and condition involved in the search process.

Concept	Combination of search terms and condition
Use of Virtual reality	virtual reality OR immersive virtual environment
	AND
Place settings	indoor environment
	AND
Patterns of Biophilic Design	biophilic design OR biophilia OR green wall OR potted plants OR indoor plants OR nature view OR nature sound OR greenery OR non-rhythmic sensory OR thermal variability OR airflow variability OR dynamic light OR diffuse light OR biomorphic forms OR wood OR natural material OR complexity and order OR prospect
Time period	no initial time restriction - January 2024
Language	English

2.2. Eligibility and inclusion steps

The Eligibility phase aimed at identifying the documents with the highest potential for the objectives of the present review. Based on the full text content, articles have been excluded from this review when they met the following criteria:

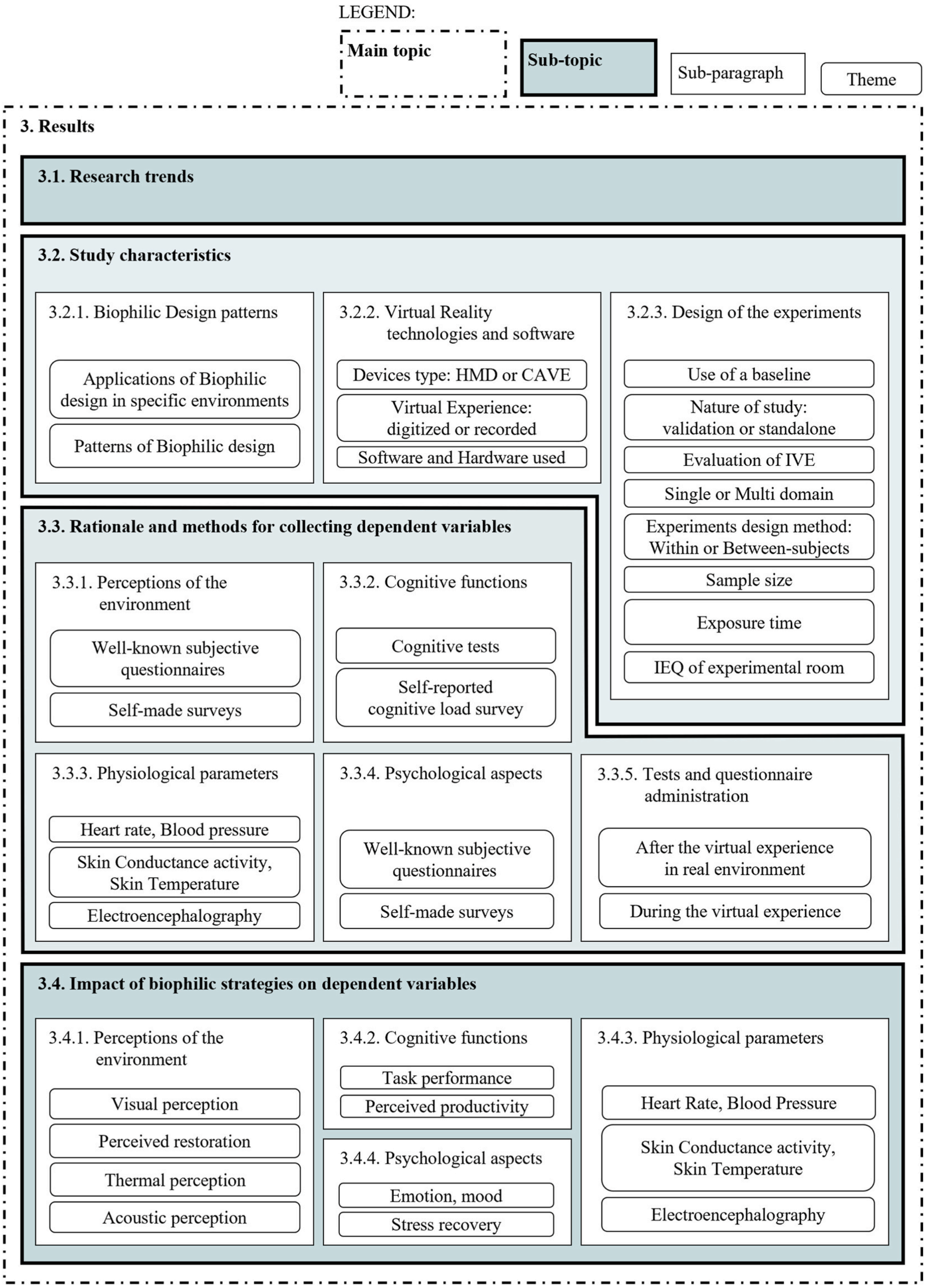

Fig. 2. Structure of the analysis of the articles covered by this review.

- Studies employing non-immersive or semi-immersive virtual environments (e.g., photo or screen-based stimuli);
- Papers unrelated to cognitive, perceptual, physiological, or psychological pathways;
- Inappropriate environments (e.g., outdoor) and building typologies (e.g., hotels, religious places, shops or commercial buildings);
- Experimental activities lacking biophilic patterns.

At the end of this phase, a total of 47 articles were gathered. Finally, a thorough evaluation of the full texts of these articles (Inclusion phase), incorporating the previously established exclusion criteria, resulted in the selection of 31 articles for a meticulous analysis of the state-of-the-art related to the objectives of the review (see Appendix A containing the finalized literature).

2.3. Data extraction process

The process of data extraction was conducted using Microsoft Excel, with one team member performing the initial extraction and a second member subsequently verifying the accuracy and completeness of the extracted data.

The Tables in Appendix A summarise the main information related to investigated studies in terms of methodology design and dependent variables data collection, analysed and discussed respectively in Sections 3.2 and 3.3. In particular, the following synthetic data on the methodology design has been extracted and tabulated in Table A. **1**: year of publication, VR technology employed; indoor comfort domain of the study (i.e., single-domain, multi-domain, or crossed effect); experimental design (i.e., within or between-subjects); participants sample size; exposure time to a virtual scenario; indoor space typology (i.e., working, residential, school, hospital); independent variables (i.e., biophilic pattern: Nature in the space, Natural analogues, Nature of the space); IBE validation against real or 2D settings; data collected to establish the "ecological validity" of the VR models (i.e., sense of immersion and presence, Cybersickness).

In addition, the following information on methods for collection of dependent variables were extracted and tabulated in Table A. **2**: perceptions domain investigated (i.e., acoustic, visual and thermal perception, perceived restoration); physiological parameters measured; psychological aspects investigated; methods to evaluate cognitive performance and load. Finally, the main outcomes from the research in terms of the impact of biophilic strategies on dependent variables are reported and analysed in Section 3.4.

3. Results

This section reports the results of the literature review to provide a comprehensive picture of the research done on BD through IVE. Despite the number of available articles is not very extended, they are highly diversified in terms of dependent variables investigated, methods used, and outcomes drawn. This section then aims, on one side, to find a synthesis of the main outcomes and concepts, and, on

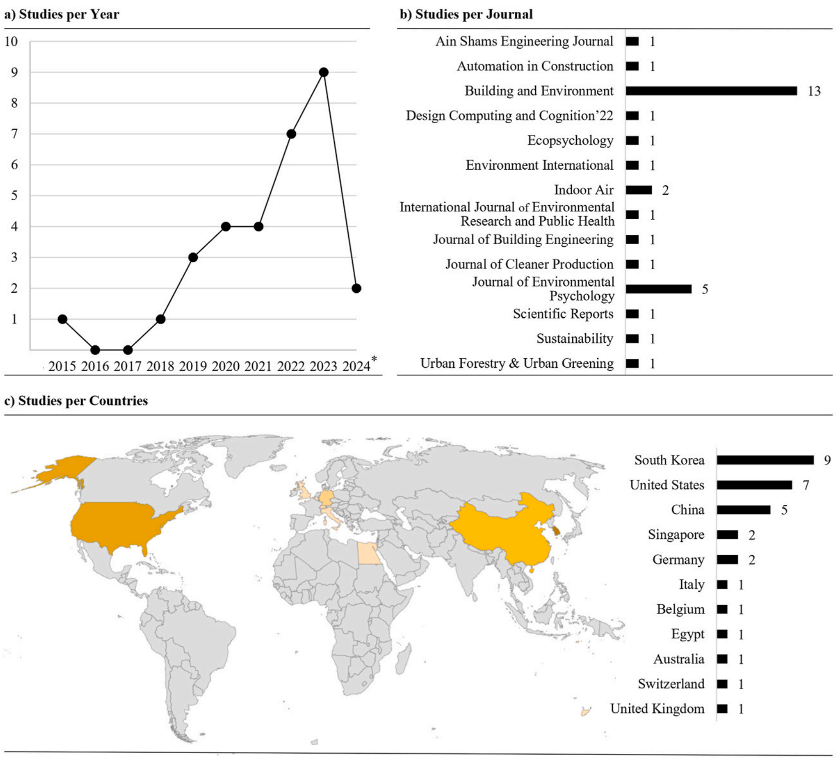

Fig. 3. Number of studies on virtual IBEs per year between 2023 and *January 2024 (a), per journals (b), and per countries (c).

the other one, to provide a comprehensive and detailed overview of the research done on the topic, by easily tracking the specific methods and results of each study.

In particular, the reader can eventually navigate between the general research trends (Section 3.1); the studies characteristics (Section 3.2) in terms of investigated biophilic patterns (Section 3.2.1), the tools used to create virtual environments (Section 3.2.2) and the experimental designs (Section 3.2.3); the types of dependent variables (i.e., object of judgement) and the methods of investigation within the virtual experience (Section 3.3) and the outcomes in terms of recorded influence of biophilic interventions on the dependent variables previously identified (Section 3.4) (Fig. 2).

The organization of the core paragraphs 3.3 and 3.4 follows the same structure, based on the retrieved four areas of investigation: perceptions of the environment, physiological parameters, psychological parameters, and cognitive functions.

3.1. Research trends

The reviewed articles are presented in this paragraph highlighting the overall research trends in terms of publication date, scientific sector, and geographical distribution.

Firstly, as shown in Fig. 3a, the whole sample of documents was published between 2015 and 2024 (part year), and mostly (n = 22, 71 %) concentrated in the last four years (2021–2024), pinpointing the emerging interest in BD research through VR. Indeed, this research field is relatively new because the possibility of creating highly accurate, realistic and effective virtual environments relates to recent technological advancements in hardware, software, and wireless tracking technology [42]. In particular, the improvement of computing speed and processing power have enabled the creation of more complex and realistic renderings, suitable to properly simulate varying intensities of natural light and shadow that often occur in biophilic environments. Moreover, advancements in algorithms for texture mapping allow to virtually simulate texture of natural materials with high fidelity.

Secondly, the disciplinary fields of journals where the reviewed studies are published are dominantly architecture and engineering, with a small portion that instead belongs to the psychological and social sciences sectors (Fig. 3b).

Thirdly, Fig. 3c shows the geographical distribution of papers in this topic, with research efforts mostly concentrated in countries like the South Corea (n = 9, 29 %), United States (n = 7, 23 %) and China (n = 5, 16 %). A limited geographical representation can be acknowledged. A possible explanation relies on the fact that academic interest in Biophilic Design is particularly relevant to highly urbanized countries where individuals spend a significant amount of time indoors in living and working settings. In these environments, there is a growing need to reconnect with nature to enhance individuals' health, well-being and productivity, which makes BD a cutting-edge topic for researchers. In those countries, the high levels of urbanization, the need for human-nature connection and greater access to effective virtual infrastructure enhance the interest in Biophilic Design and Virtual Reality intersection leading to a predominance of research activities on this topic. For instance, the significant scientific research contribution produced in China is growing accordingly with their strong adoption of advanced technology in construction disciplines as a driver of economic growth [43]. This attitude leads to emerging areas, such as BD in VR, developing technological innovation and progress in the field.

3.2. Studies characteristics

This section illustrates the methodological features of the reviewed papers in terms of investigated biophilic patterns, of tools and approaches used to create the virtual settings, and of experimental design of the studies, in order to identify the most recurring methodological directions.

3.2.1. Biophilic design patterns

Fig. 4 represents the percentage distribution of the biophilic patterns investigated in the papers, according to the distinction into

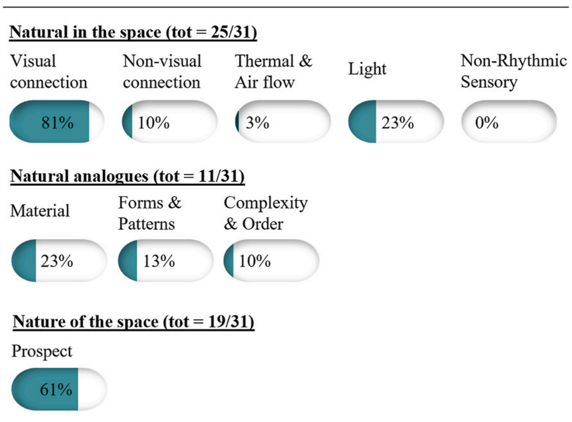

Fig. 4. Biophilic pattern investigated by the selected papers.

the 3 main categories: Nature in the Space, Natural Analogues, and Nature of the Space.

Concerning the **"Nature in the Space"**, the most considered biophilic pattern is "Visual Connection with Nature" (81 % of the studies), due to the principal capability of IVEs to reproduce highly detailed visual scenarios. Researchers focused on visual elements such as view of greenery and sky through windows [44–57], potted plants [44,45,56,58–60] or green walls [45,50,56,61–66] because these elements are easy to simulate in virtual contexts. Conversely, "Non-Visual Connection with Nature" (3 studies, 10 %) was less investigated and often in addition to the visual setting. The possibilities of modern VR allow for example an audiovisual experience, but to obtain a realistic audio stimulus this must include heads movement as we do in real life to explore the environment. Obtaining a dynamic virtual acoustic environment is particularly difficult that requires the reproduction of a 3D soundscape. Despite these challenges, some studies have attempted to enrich the virtual experience by incorporating sounds or even scents: Shin et al. [52] added birdsongs and wet soil smells to an open window visual scenario, Mahrous et al. [59] reproduce water sounds through the VR headset, while Latini et al. [74] combined the visual connection with nature with birdsong recordings. None of the reported studies investigated the "Non-Rhythmic Sensory Stimuli". Considering the "Thermal & Airflow Variability" category, only one study investigated the impact of a low-speed fan to simulate natural ventilation [59]. Finally, the "Dynamic & Diffuse Light category" was investigated by 7 studies (23 %), where the independent variable was the presence or absence of natural daylight through the windows in IVE [45,56,59,67,68]. Additionally, Sharam et al. [51] introduced a scenario that contained a window with shutters, which allowed for daylight infiltration while blocking the view of nature, while Chamilothori et al. [49] investigated the impact of a clear sky with high or low sun angle versus an overcast sky.

Regarding the **"Natural Analogues"**, most cases investigated the "Material Connection with Nature" (23 %), focusing on the use of wooden floors, walls, columns, beams or ceilings [44,50,59,69,70], or other unspecified natural materials [45,56]. "Biomorphic Forms & Patterns" were reproduced by Yin et al. [45,56] in furniture design, by Kim et al. [50] employing a wavy patterned ceiling, and by Tawil et al. [71] with curved contour conditions in indoor living rooms. The "Complexity & Order" pattern has been investigated by three papers. Chamilothori et al. [49] studied the complexity of a façade pattern variation with small, irregularly distributed openings, Renterghem et al. [53] assessed the combination of different trees and greenery species richness, while Tan et al. [72] identified the influence of fractal diffusion structures on visual preferences.

Concerning "**Nature of the Space"**, the "Prospect pattern", that is the only one considered in this review for this category, was evaluated by more than half of the reviewed scientific articles (19 studies, 61 %), by providing outdoor views through windows in the IBE. In particular, seven studies compared settings with and without windows [44–46,51,52,59,68], three studies investigated the effects of different amounts or quality levels of outdoor views through a window [49,53,54], two studies created a virtual environment

Table 3

Software and Hardware used in the selected papers. M = virtual modelled experience, R = virtual recorded experience.

Ref.	Year	Virtual experience	Software used for 3D modelling					Software used for VR scene implementation				
			Rhinoceros	Revit	SketchUp	Cinema 4D	3ds Max	Unity	Unreal Engine	Twinmotion	V-Ray	Other
[68]	2015	M		•			•					•
[44]	2018	R										
[56]	2019	M	•					•				
[75]	2019	M		•		•		•				
[57]	2019	M			•		•		•			
[45]	2020	M	•					•				
[77]	2020	M										
[47]	2020	R										
[48]	2020	M			•				•			
[61]	2021	M			•				•			
[71]	2021	M					•	•				
[62]	2021	M			•				•			
[63]	2021	M					•					
[49]	2022	M						•				
[64]	2022	M	•					•				
[78]	2022	M							•			
[51]	2022	M	•							•		
[65]	2022	M						•				
[40]	2022	R										
[54]	2022	R										
[58]	2023	M						•				
[69]	2023	M			•					•		
[79]	2023	M										
[53]	2023	M	•	•						•		
[60]	2023	M										
[74]	2023	M		•			•	•				
[66]	2023	M			•						•	
[67]	2023	M			•							•
[70]	2023	M			•							•
[72]	2024	M										
[80]	2024	M	•					•				

with different window size ratios [57,73], finally one work evaluated the impact of viewing location (close, middle, far) on view perception [47]. However, the Prospect feature does not only include the possibility of viewing from inside to outside, but also the optimization of indoor vistas. Indeed, some studies investigated spatial features, such as open spaces or the presence/absence of partitions [56,67,74]. Furthermore, Mihara et al. [60] evaluate the effects of spaciousness (i.e.: room volume and window configuration factor), while Cha et al. [75] assess the spatial perception of ceiling height. Finally, Jung et al. [66] designed an IVE with an anamorphic illusion feature applied to the wall, allowing the visual experience of an additional prospective space filled with nature.

From the outlined picture, the prevailing interest in visual aspects related to BD is evident, in particular Visual Connection with Nature and Prospect patterns. This is justified by the full exploitation of the potential of immersive virtual reality, whose advantage is the ease of use of different visual scenarios.

3.2.2. Virtual reality technologies and software

Among the reviewed studies, employing immersive systems, the clear majority used binocular Head Mounted Displays (HMDs) (28 studies, 90 %), due to the ease of use and affordable cost, combined with an excellent result in terms of realism and sense of presence. Only three works adopted projection-based immersive systems. In particular, Wong et al. [76] allowed participants to move around and change their views by interacting with a Cave Automatic Virtual Environment (CAVE) using a joystick controller, while Shin et al. [52] used a static position for the subject sitting on a chair in a three-sided CAVE. Finally, Tan et al. [72] performed the experiment in a virtual simulation laboratory with a hemispherical screen.

The combinations of software used by the reviewed papers are reported in Table 3. To design the virtual experience, most of the reviewed studies digitized the indoor scenes by using software for 3D modelling and rendering then virtualized them by using software for VR implementation. This type of virtual modelling experience is the most widespread in the papers (27 studies, 87 %), as it allows a fast manipulation of the indoor environment and an easy control of the design variables. 4 studies did not model the virtual setting and

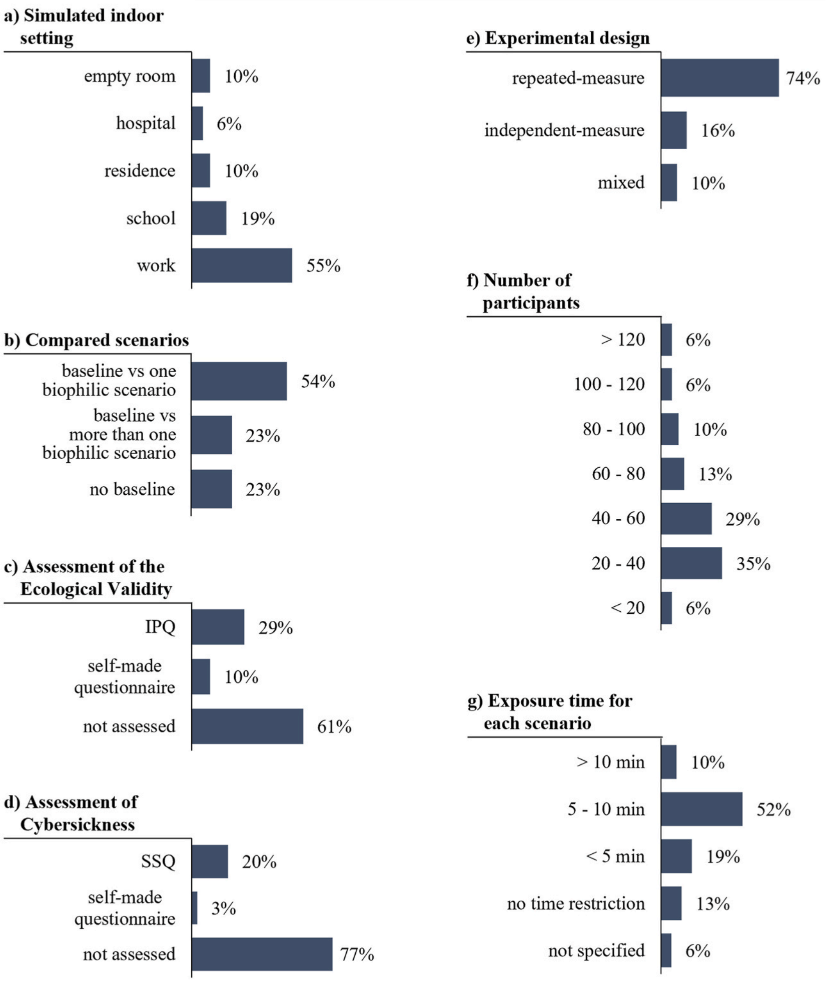

Fig. 5. Number of papers (%) per (a) simulated indoor setting, (b) compared scenarios, (c) assessment of the Ecological Validity, (d) assessment of Cybersickness disorders, (e) experimental design, (f) sample size, (g) exposure time for each scenario.

preferred recording the scenes using 360-degree field-of-view photos [47,65] or videos [44,52].

3.2.3. Design of the experiments

Concerning the specific features of the experimental methods adopted in the reviewed IBE studies (summarised in Table A. 1), the following key remarks arise:

- **Simulated indoor settings (see Fig. 5a).** The records focused on working environments (55 %, 17 studies [45,47–49,51,54,56–58,61–63,68,72,74,75,80]), schools (19 %, 3 studies in university classrooms [44,50,59] and 4 in common areas [44,46,52,70]), residential buildings (10 %, 3 studies [53,69,71]) and healthcare facilities (6 %, 2 studies [66,81]). Three additional studies do not specify the type of environment, experimenting an empty virtual room without furniture or objects other than the biophilic elements [60,64,65].
- **Comparison with a "baseline" (see Fig. 5b).** The majority of reviewed studies assessed the effect of a given biophilic condition on occupants based on a comparison with a "baseline", i.e. a scenario without biophilic stimuli. Among them, 7 studies (23 %) compared a non-biophilic baseline with just one biophilic scenario [44,58,64,68,71,77,79], while the remaining works (17, 54 %) compared at least one non-biophilic scenario with different levels or combinations of biophilic features. Nevertheless, other 7 studies (23 %) did not define a baseline condition and performed the evaluation based on the comparison of different quantity and quality of biophilic conditions [47–49,53,54,57,72].
- **IBE Validation.** An accurate representation of the indoor environment and a fully immersive experience are crucial for obtaining reliable users' feedback. The adequacy of VR in replicating physical settings can be obtained by making a preliminary comparison of collected results between the real and the virtual settings [23]. Most of the reviewed papers did not preliminary perform a "validation" study comparing results obtained in the IBE and the real counterpart. Only 4 research (13 %) included a validation study [44,46,57,68]. 2 studies (6 %) intended to validate the IVE by a comparison with a screen-based stimulus [50,74].
- **Assessment of the "Ecological Validity" of the virtual model (see Fig. 5c).** This refers to the ability of the IVE to accurately recreate real-world experiences. Assessing Immersion and Presence helps determine the degree to which users feel immersed and present in the virtual world, thus contributing to the overall quality of the user experience and the effectiveness of the IVE application. The sense of presence develops from the construction of a spatial-functional mental model of the virtual environment and can be characterized by three main concepts: spatial presence, involvement, and sense of realism [82]. The Ecological Validity can be assessed by self-reports from participants concerning the sense of presence and immersivity [19]. More than half of the studies did not provide a measure of the participants' sense of presence and immersion within IVE (19 studies, 61 %). 29 % of the reviewed studies used items from the Igroup Presence Questionnaire (IPQ) developed by Schubert et al. [82]. Other studies design their own questionnaires. Heydarian et al. [68] mixed self-made questions with questions adapted from Witmer et al. [83]. In the experiment of Renterghem et al. [53], people were only asked to rate the overall realism of the virtual reality experience using a 5-point scale ("not at all realistic", "little realistic", "neutral", "realistic", "very realistic"). Zeng et al. [67] invited a subset of participants ($N = 42$) to conduct a pre-test where they were asked to rate the realism of the virtual scene in comparison with pictures.
- **Assessment of Cybersickness disorders (see Fig. 5d).** The success of VR applications also depends on the Cybersickness, a form of motion sickness experienced in VR environments. Assessing Cybersickness helps identify potential causes of discomfort and allows for the refinement of VR experiences to minimize adverse effects due to motion sickness and eye strain [84]. It can be evaluated by self-reports from participants [19]. 20 % of the studies used the Simulator Sickness Questionnaire (SSQ) [85], or a similar one concerning a list of disorders (e.g., eye strain, headache, vertigo) assessed on a Likert scale. More than half of the studies did not provide a measure of the participants' Cybersickness symptoms (24 studies, 77 %). Wong et al. [74] asked all the participants to assess the dizziness level and to express a preference between a traditional approach and the VR-based approach.
- **Sensory inputs, comfort domains and cross-effects.** In the context of exploring the impact of biophilic interventions, a distinction is made between studies focusing on a single domain and those examining several comfort domains ("multi-domain") and cross-effects induced by multiple independent sensory stimuli. Only 3 studies (10 %) performed an investigation that evaluated physiological, psychological, cognitive, and perceptual aspects across different domains. Shin et al. [52] explored the restorative qualities of the visual connection with nature with the addition of biophilic sounds and smells, while in the study of Latini et al. [86], three visual factors were combined with three acoustic scenarios. In addition, Mahrous et al. [59] measured the students' level of satisfaction when exposed to many biophilic sensory inputs: visual, acoustic, thermal and airflow. 5 studies (16 %) explored the cross-effect of multiple sensory dimensions, investigating interactions between domains (e.g., the impact of visual conditions on thermal perceptions). Sedghikhanshir [64] and Kim [69] evaluated the influence of visual connection with nature on human thermal perception, while the aim of the study of Renterghem et al. [53] was to explore the effect of greenery views on noise annoyance. In addition, Jeon et al. [54] investigated the crossed effects of audio-visual attributes on the quality of a virtual open-plan office environment, and similarly, Mihara et al. [60] evaluated the effects of green coverage ratio and spaciousness on visual, acoustic, and thermal comfort. The rest of the reviewed studies conducted experiments adopting a single-domain approach (23 studies, 74 %).
- **Experimental design (see Fig. 5e).** Over 74 % of reviewed studies used a repeated-measure design, with the remainder an independent-measure design [45,52,65,66,74], except for 3 articles that used a mixed design: that of Zeng et al. [67], where each participant experienced three different VR scenarios out of nine, that of Chamilothori et al. [49], where the design consisted of between-subjects factors (sky type and social/working context) and a within-subjects design was employed to evaluate six façade

geometry variations, and that of Latini et al. [86], which employed three between-participants levels of visual stimuli and three within-participants levels of acoustic factors.

- **Size of participants' samples (see Fig. 5f).** In the analysed papers, it frequently turned out to be smaller than the initially recruited sample size. This discrepancy can be attributed to the exclusion criteria of each study. More than half of the studies (65 %) conducted experiments with a sample size of 20–60 participants, while the smallest sample size was 15 participants [63] and the largest sample size was 256 [49] (combination of an experiment conducted in Switzerland (118 participants) and on in Greece (138 participants)).
- **Duration of exposure time in the IVE (see Fig. 5g).** It significantly varied across experiments (Fig. 5), with a prevailing 5–10 min exposure time noted in 52 % of the articles, given a minimum of 30 s [50] and a maximum of 20 min [63]. Furthermore, 4 works decided not to limit the exposure time [49,54,70,74]. Finally, two articles (6 %) did not specify the exposure time for each virtual scenario [51,68].
- **IEQ in the study room.** Studies largely excluded information identifying the real environmental conditions of the room/building where the experiment was conducted (16 studies, 52 %). Only 15 articles monitored IEQ parameters and reported the indoor environmental conditions of the VR lab, such as temperatures (42 %), relative humidity (35 %), light intensity (19 %), air velocity (6 %) or carbon dioxide (13 %) and $PM_{2.5}$ concentrations (6 %).

3.3. Rationale and methods for collecting dependent variables

A preliminary analysis was carried out to identify the types of dependent variables investigated in the reviewed studies.

As shown in Fig. 6, occupants' **perceptions** were the most investigated (21 studies, 68 %) among the reviewed literature. For this aspect, a distinction is made between the acoustic, visual and thermal comfort domains, the specific perception of biophilic elements (e.g., aesthetic rate of the greenery, self-reported connection with nature), and the perceived restoration potential of the environment. Among these aspects, the least investigated are the acoustic and thermal domains, as well as biophilia perception (3 studies, 10 %). Several studies evaluated occupants' **psychological aspects**, such as emotion and stress (16 studies, 52 %), or collected **physiological parameter measurements** (16 studies, 52 %), to validate subjective responses and results with objective data. Finally, **cognitive measurements** were the least collected data (14 studies, 45 %), with a distinction between several functions: attention (10 studies, 32 %), memory (8 studies, 26 %), inhibition and flexibility (7 studies, 23 %), creativity (3 studies, 10 %), and comprehension (2 studies, 6 %).

As a result, four categories were highlighted, which structured the sub-paragraphs: perception of the environment (section 3.3.1), cognitive functions (section 3.3.2), physiological parameters (section 3.3.3), psychological aspects (section 3.3.4). This distinction reflects the different nature of the dependent variables investigated in reviewed articles. Indeed, it is noteworthy that most of the studies (74 %) do not focus on a single aspect, but rather consider multiple user responses in parallel, also in an attempt to find a correlation among them.

In addition, the administration of methods for data collection within the virtual experience are explored in sub-section 3.3.5.

3.3.1. Perceptions of the environment

The human perceptual mechanisms instinctively allow the assessment of the experienced environment depending on its visual, thermal, acoustic and restorative properties. As a result, perception is fundamental in BD studies because it provides information about the subjective experience within a space. Participants' perceptions in response to various IBE scenarios were evaluated through several well-known subjective questionnaires, or, in some cases, designing specific self-made surveys, in order to detect the following aspects:

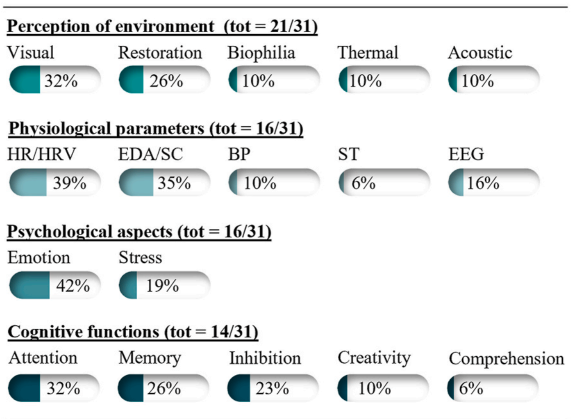

Fig. 6. Distribution of the investigated aspects among the reviewed studies.

- **Visual and spatial perceptions of the indoor environment.** A great number of reviewed articles focused on these topics (10 studies, 32 %), as they are the most immediate factors that impact the occupant. Researchers used satisfaction surveys to investigate sense of privacy, visual comfort, aesthetic assessment, sense of inner space and openness, reflecting the interest of the studies in capturing how occupants perceive the organization and spatiality of indoor environments. The *Affective and Spatial Experience* (ASE) [71] is the most adopted questionnaire, where, using 11-point numeric scales labelled with opposing descriptive adjectives on each side, participants provide self-reports on bipolar dimensions, including orderliness and naturalness aspects.
- **Perception of the biophilic design.** It was evaluated by only 3 studies (10 %), where participants were asked to rate their connection with nature and their preference for biophilic patterns using self-reported scores [44,56] or by assessing the aesthetic value of greenery [53]. In particular, in the study of Yin et al. [44], a specifically index, named *Biophilic Interior Design Index* (BIDI), was developed demonstrating an effort to assess the overall biophilic quality of indoor environment and providing direct feedback on the effectiveness of biophilic interventions.
- **Thermal perception.** 3 out of the reviewed articles (10 %) focused on this aspect, thus the experiments were conducted in a climate chamber or in a conditioned room. While Mihara [60] et al. asked participants to rate their thermal comfort using a 5-point scale (dissatisfied to satisfied), two other studies employed the self-reported votes of thermal sensation, comfort and preference according to the ASHRAE Standard 55 [64,69], indicating a methodological approach focused on quantifying the thermal experiences.
- **Acoustic perception.** This topic received limited attention among the reviewed studies (3 studies, 10 %). The questionnaires used in the studies addressing acoustic perception to understand the impact of greenery views on self-reported noise annoyance [53], overall acoustic satisfaction [60] or the extent to which various scenarios aligned with semantic expression words related to hearing (i.e., "loud", "variable", and "reverberant") [54]. The focus on how biophilic views impact the acoustic perceptions suggests an interest in understanding the multi-sensory integration of BD, where visual elements may also influence acoustic experiences, but still remains less investigated.
- **Perceived restoration potential of the indoor environment.** Nearly all studies exploring this topic utilized the *Perceived Restorativeness Scale* (PRS) [87], or the *Restorative Outcome Scale* (ROS) [40]. The PRS is based on ART [10] and it is a subjective questionnaire commonly used to measure the extent of a restorative environment, together with ROS which has a broader theoretical foundation, incorporating elements from both ART and SRT [11]. Specialized versions of the PRS have been created for specific environments, such as hospitals, known as the *Hospital Indoor Restoration Scale* (HIRS) [67]. Additionally, some researchers have developed personalized scoring items by integrating multiple evaluation indicators from the PRS [70] highlighting the need to adapt these tools to better capture the regenerative qualities of different contexts.

3.3.2. *Cognitive functions*

According to ART natural elements offer stimuli that capture individuals' attention effortlessly, allowing mental fatigue restoration. As a result, the capacity for performing cognitive tasks is assumed to be greater in biophilic environments. Cognitive functions are mainly investigated using quizzes and tests related to several mental abilities, including attention, mental flexibility, comprehension, creativity, and working memory.

Attention is an indicator of the ability to quickly focus on relevant stimuli within the environment. It has been categorized into two

Table 4
Summary of cognitive test used by reviewed articles.

Cognitive function	Cognitive Test	Ref.
Attention	◦ Visual reaction time task	[63,89]
	◦ Auditory reaction time test	[62]
	◦ Stroop color-word test	[63,74,86,89,90]
	◦ Skip counting task	[71]
	◦ Continuous performance task	[51]
	◦ Simple response time task	[51]
	◦ N-back task	[51]
	◦ Wisconsin card sorting	[59]
	◦ Trail making test	[59]
	◦ Identification task	[68]
Flexibility	◦ Category-letter switching task	[51]
	◦ Wisconsin card sorting	[59]
	◦ Trail making test	[59]
	◦ Magnitude-parity test	[86]
Working memory	◦ Backward digit span task	[58,89]
	◦ Visual working memory test	[46]
	◦ Ospan test	[86]
	◦ Auditory backward digit span	[54,62]
	◦ Working memory task	[63]
	◦ Wisconsin card sorting	[59]
	◦ Trail making test	[59]
Creativity	◦ Guilford's alternative uses test	[51,58,90]
Comprehension	◦ Reading tasks	[68,75]

main components: sustained attention and executive attention. Sustained attention refers to the ability to internally maintain control in the absence of significant external stimuli. Conversely, executive attention involves the allocation of attentional resources to goal-directed tasks and the inhibition of irrelevant information [51]. In particular, executive attention implies more specific cognitive processes such as inhibitory control. Working memory is a cognitive system responsible for the temporary storage and manipulation of information necessary for complex cognitive tasks, while creativity, is the capacity to generate novel and valuable ideas, providing insights into divergent thinking abilities [88]. Finally, comprehension is the cognitive process of extracting meaning from information received through language or reading modalities, involving critical thinking to interpret relationships and integrate information.

Table 4 summarizes the cognitive tests used by the reviewed articles, grouped by the measured cognitive function.

Besides research employing tests to investigate cognitive performance, 3 studies used subjective workload assessment questionnaires to measure the perceived workload experienced by individuals. Yeom et al. [62] employed the *NASA-TLX* questionnaire to evaluate mental and physical demand and frustration levels in each experimental scenario. Similarly, Mihara et al. [60] asked participants to evaluate on a 5-point scale the level of their concentration, productivity, and motivation. Also, Wong et al. [76] used the same 5-point scale to examine the impacts of different office design approaches on the participants' concentration.

3.3.3. Physiological parameters

According to SRT, our innate physiological stabilization due to exposition to nature derives from the facts that humans evolved from the natural environment in the prehistoric era [11].

Numerous studies have investigated the calming impact of elements associated with biophilia by assessing the physiological responses of individuals in IVE (16 studies, 52 %). These studies can be generally distinguished depending on the type of physiological measurements employed. In particular, as shown in Fig. 6, heart rate (HR) and heart rate variability (HRV) were the most collected data measured by 12 studies (39 %), followed by Electrodermal activity (EDA) or Skin Conductance (SC) with 11 studies (35 %). Sometimes, such parameters were accompanied by additional physiological measurements like Blood Pressure (BP) (3 studies, 10 %) or Skin Temperature (ST) (2 studies, 6 %). Furthermore, 5 studies (16 %) assessed neurophysiological responses using Electroencephalography (EEG).

Table 5 outlines the expected trend for each physiological parameter given a stress reduction. Notably, ST is excluded from the table due to no correlation with stress, as BD studies principally used it as an indicator for analysing the individual's thermal sensation [64, 69].

3.3.4. Psychological aspects

The term "Biophilia" was first coined in the field of **psychology** [91] and has then been applied to different disciplines, including engineering and architecture giving life to BD. The investigation of the psychological response mechanism is therefore a primary aspect for experiments addressing this topic. Emotional responses to an environment are widely investigated through self-assessment questionnaires, which can be easily administered also in studies that use VR. In 16 studies, in addition to physiological measures, subjects were asked to rate their emotional state (42 % of the revied papers) and stress level (19 %) through the following self-assessment questionnaires, which are widely used in psychology research:

- **Emotions.** The most used questionnaire was the *Positive and Negative affect scale* (PANAS) [46,47,51,58,62,66], which includes 10 items that measure positive emotions and moods (e.g., enthusiasm, energy, joy) and another set of 10 items referring to negative feelings (e.g., sadness, grief, fear), to be rated on a 5-point Likert scale. This dual measurement may be one of the best ways to account for the overall emotional human balance, helping to identify which combinations of biophilic elements promote most positive or negative emotions. However, the field of psychology offers a variety of questionnaires different from PANAS to explore the psychological responses triggered by connections with nature as well. Consequently, the remaining reviewed studies opted for tools that provide similar but alternative perspectives on how BD influences mood. In 2 other studies [47,60], the mood was evaluated using the *Circumplex model*, a psychological framework where emotions are organised in relation to two dimensions: valence (positive or negative) and arousal (high or low). A similar approach was adopted by Cha et al. [75], who asked questions about affective responses including six adjectival pairs on semantic-differential scales (e.g., "calm-excited"). Another study used the *Profile of Mood States* (POMS) [48], which consists of five negative subfactors (i.e., "depression", "confusion", "tension", "anger", and "fatigue") and one positive subfactor (i.e., "vigour") to delve into specific momentarily changing emotional states. The use of *Zuckerman Inventory of Personal Reactions* (ZIPERS) [58] was also detected, where the subject indicates on a 5-point scale the degree

Table 5
Correlation between physiological parameters and stress. ↑/↓: increase/decrease during stress reduction.

Physiological parameters	Correlation with stress reduction	Ref.
HR	↓	[56,60]
HRV-LF/HF	↓	[72]
HRV-SDNN	↑	[72]
HRV-RMSSD	↑	[60]
EDA/SC	↓	[44,47,65,67,72]
BP	↓	[56]
EEG alpha	↑	[66,78]
EEG beta	↓	[66,78]

to which five items (i.e., “fear”, “positive affect”, “anger/aggression”, “attentiveness/interest”, and “sadness) describes the way he feels, and the *Self-assessment manikin questionnaire* (SAM) [67], where the higher the SAM score, the more the participant's emotion tends to be positive and associated with high arousal, similar to the *Momentary affective state* (MAS) [71], assessing different emotions domains.

Finally, 2 studies created their own self-assessment questionnaire. In particular, Yin et al. [44] used a self-made mood score, while Li et al. [65] chose three indicators that characterized the level of subjective negative emotions (i.e., “anxiety”, “tension” and “avoidance”) and employed a self-report scale, which was a modified version of the *Visual Analogue Scale* (VAS) to assess these emotions.

- **Stress.** Over 80 % of the articles did not use a stressor to create mental fatigue in subjects in the pre-restoration phase. Conversely, 6 studies used a stressor to investigate the hypothesis that mental recovery from stress and anxiety would be greater after exposure to biophilic environments, given the basis of SRT [11]. Among these studies, one used emotionally negative evocative photographs [65], 4 studies required to complete a cognitive test [47,48,60,67], and 1 study employed memory task and arithmetic task in an untidy office environment with background noises [45].

To measure changes in stress state, 3 studies used the *State-Trait Anxiety Inventory* (STAI-s) [45,61,66]. This questionnaire evaluates the temporary and subjective anxiety that can change according to the environment. In 3 other studies [44,47,60] stress recovery was evaluated using self-reported stress questions.

3.3.5. Test and questionnaires administration

Cognitive tests and self-reporting questionnaires and interviews can be administered after or during the virtual experience, thus somehow impacting the reliability of the results obtained. Fig. 7 represents the percentage distributions of studies employing the different administration methods, among the total of studies using cognitive tests (14) and questionnaires (30). In particular, while the majority of studies (71 %) employ cognitive tests administered within the immersive virtual environment, fewer than a third (27 %) do so with questionnaires. The following administration methods arise:

- **Both questionnaires and cognitive tests administered during the virtual session.** The reviewed studies employ different modalities to enable data collection in the IBE. For example, during the experiment of Jeon et al. [54], a survey was conducted in the form of a Graphical User Interface (GUI) within the VR, and each subject was asked to respond with a controller. In Wong et al. [74], participants moved around and changed their views by interacting with the virtual office using a joystick controller, and the cognitive test was presented on a virtual computer screen. In addition, virtual co-workers have been created to present multiple-choice questions to the participants using a graphical dialogue. To design a seamless transition between the virtual experience and the questionnaire, Cha et al. [75] used an online survey on a virtual screen, and participants were invited to orally answer the questions. In other works, participants remained in the immersive environment while the questionnaire was verbally administered [49,51,64].
- **Only cognitive tests administered during the virtual session.** This approach has been preferred to reduce the immersion time. In 5 studies [45,48,56,62,68] participants were virtually exposed to an indoor environment where performed a cognitive test in a virtual desktop, then completed a questionnaire in the real environment.

Conversely, Mostajeran et al. [58] administered two cognitive tasks within VR using pre-recorded audio providing instructions and asked participants to verbally answer. For the evaluation of the task, a paraphrasing transcription of the answers based on the audio files was used. Subsequently, participants took off the HMD and filled out a questionnaire.

Similarly, during the VR session, Tawil et al. [71] displayed a cognitive test on a wall-mounted screen in the virtual room, asking participants to pronounce the results out loud, while answers were manually collected by experimenters. Later, questionnaires

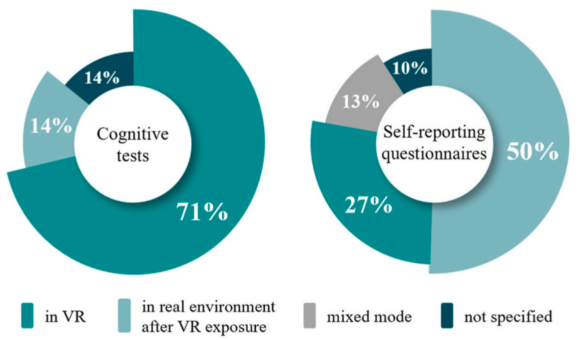

Fig. 7. Percentage distributions of studies employing the different administration methods, among the total of studies administering cognitive tests (14) and questionnaires (30).

assessing the affective and spatial experience were administered in a virtual screen, while IPQ and SSQ questionnaires were provided pre- and post-VR sessions, in the real environment.

3.4. Impact of biophilic strategies on dependent variables

This section aims to present the results obtained by reviewed studies in terms of impact of various indoor biophilic scenarios (i.e., stimuli) on for the dependent variables identified in the preliminary analysis reported at the beginning of Section 3.3: perception of the environment (section 3.4.1), cognitive functions (section 3.4.2), physiological parameters (section 3.4.3), psychological aspects (section 3.4.4).

3.4.1. Perceptions of the environment

Several studies highlight a positive impact of BD, especially in terms of visual satisfaction and restoration, while the influence of biophilic strategies on indoor thermal and acoustic perception is less established, as detailed in the following points:

- **Visual and spatial perceptions.** All the reviewed studies report benefits of BD on this aspect. Chamilothori et al. [49] discovered that the complexity of the façade geometry has an impact on the visual appraisal of the space (i.e., perceived complexity, brightness, spaciousness), and found that it positively influenced the reported satisfaction. In the findings of Cha et al. [75], participants preferred a higher and open ceiling, perceiving it as more spacious and attractive. Additionally, in Jeon et al. [54], visual satisfaction, visual privacy, and speech privacy showed higher rates in the good view than in the bad view scenarios. Surprisingly, the results of Tawil et al. [71] suggest that the presence of curved furniture and details did not significantly improve visual and spatial perception despite a visual preference for softer edges typical of natural elements is highlighted from biophilic theories. Only in terms of perceived privacy, large openings or open spaces could have a negative impact. In two studies [57,73] participants expressed a significantly higher satisfaction in terms of visual comfort, sense of inner space and openness in scenarios with higher window-to-wall ratio, even if showed a lower satisfaction in terms of sense of privacy. Wong et al. [76] indicated that lower partitions in office design gain a lower satisfaction level.
- **Perception of the biophilic design.** Concerning the evaluation of BD perception, Yin et al. [44] discovered that the room with *natural elements* obtained the highest BIDI score and in a second study [56], participants reported a stronger connection with nature in the *natural elements* scenario, than in the *natural analogues* scenario.
- **Thermal perception.** It could be indirectly influenced by the presence of biophilic patterns, however results collected by the literature to date are quite contrasting. According to Sedghikhanshir et al. [64], participants' thermal comfort was significantly better between a virtual room with a green wall and a non-biophilic one, even if the experiment was conducted in a climate chamber under the same slightly warm condition, while a non-significant difference was observed in terms of thermal sensation and acceptability. In addition, experiment results conducted by Mihara et al. [60] indicated that there were no differences in thermal comfort satisfaction among six IVE scenarios with different levels of green coverage ratio and spaciousness. Instead, in the study of Kim et al. [69], the occupants reported a higher subjective thermal sensation in the wood scenario compared to the non-wood scenario, with the perception of warmness increasing as the level of wood application rises.
- **Acoustic perception.** Concerning this aspect, the impact of BD is similarly uneven. Studies of Jeon et al. [54] and Renterghem et al. [53] revealed that high window area ratio or the presence of rich greenery in colours and plant species had positive correlations with sound satisfaction. However, high vegetation density showed statistically significantly higher noise annoyance than when green quantities were lower [53]. These finding suggests that green quality (i.e., species richness, colourfulness, and maintenance degree) has a stronger effect on acoustic perception than green quantity, and this evidence is also supported by the study of Mihara et al. [60] where there were no notable differences in acoustic satisfaction among scenarios with varying levels of green coverage ratio combined with different room volume and window configurations.
- **Restoration.** It is a frequently reported aspect in occupants' perceptions, assumed to be present to varying extents in an environment with natural connection conditions, as originally formulated by ART [10]. Several studies highlighted the positive influence of BD on restoration by comparing a biophilic scenario with a non-biophilic one [58,79] or exploiting the possibility of VR to generate a large set of immersive scenes and find the most restorative condition. For example, Li et al. [70], investigated several wood rate and wood-application form, proving that the restorative perception of a space implanted with wood structure and wood enclosure components is stronger than other configurations. The proximity to natural views, like the sky and ground, also played a positive role, with closer views offering more restorative benefits [47]. Similar results are obtained by Shin et al. [40], which proved that the presence of a window determines significantly higher scores for ROS and PRS, than a no-window scenario, but adding natural sounds and smells to an open window did not improve these restorative effects compared to a closed window. Zeng et al. [67] focused on the restorative evaluation of a healthcare environment, finding that the best restorative design combination was medium-height side windows and semi-enclosed ward unit partitions. However, Lei et al. [63] found that, even though the green density was highest in the virtual environment, the restoration response was worse than in real conditions with small quantities of green coverage.

3.4.2. Cognitive functions

The reviewed studies provide only partial support to the idea that exposure to nature can improve cognitive abilities, especially in terms of attention, mental flexibility, working memory, creativity, and comprehension, i.e. the functions investigated by specific cognitive tests used in the reviewed articles, as listed in Table 4 (Section 3.3.2), as follows:

- **Attention.** Surprisingly, only the findings of Latini et al. [86] and Lei et al. [63] detected a statistically significant improvement in the processing speed during the *Stroop test* in case of visual exposure to an indoor natural environment, while the remaining reviewed studies obtain no benefits of BD for this cognitive function. For example, in the *visual reaction time task* and *Stroop test* administered by Yin et al. [44], improvements on attention and mental inhibition in a biophilic environment compared to the non-biophilic environment, were not statistically significant, even if participants respectively scored 2 % and 6 % higher when in the biophilic environment. However, these results may not be attributable to the use of VR because, participants performed cognitive tests both in physical and virtual biophilic environment and they exhibited similar cognitive responses. In another study of Yin et al. [56] selective attention was measured again by the *Stroop test* and participants in biophilic scenarios with natural elements showed longer reaction times, while the relative effects of natural analogues scenarios were not statistically significant. In addition, in the study of Yeom et al. [62], the participants' performance was assessed through two auditory cognitive tests in four alternative virtual scenarios, one non-biophilic and three biophilic (respectively with one small green wall, two small green walls, and a full-sized green wall covering the entire area of a single wall of the room). However, they found no statistically significant difference between the task performance in all scenarios. Similarly, no relevant variations were found on sustained attention, phasic alertness and executive attention, due to other BD patterns, such as the impact of window views of nature and daylight [51] or the effect of room contours (i.e., curved interiors vs angular ones) [71].
- **Memory.** In Yin et al. [44], short-term memory of participants improved by 14 % when they were exposed to an indoor setting with biophilic design elements (e.g., plants, bamboo floor, a window with external views of green space and river). Memory performance ratings were higher also in the study of Jeon et al. [54] related to an open-plan virtual office with a good sky view, and of Latini et al. [86] which investigated audio-visual connection with nature. Conversely, Mostajeran et al. [58] compared two memory metrics in a virtual office with and without plants, finding significant improvement only for one of them in the BD scenario [92]. Similarly, Emamjomeh et al. [46] performed a within-subject experiment with 35 college students finding no positive effect of a virtual biophilic space with a good natural view through a large window on working memory compared to a non-biophilic one.
- **Mental flexibility.** For this cognitive function, no better accuracy was detected when participants were exposed to natural sounds or view [51,86].
- **Creativity.** All studies that administered cognitive tests to investigate creativity have reported promising results in favour of IBE. The experiment of Sharam et al. [51] compared the results of *Guilford's alternate uses task* carried out in an office IVE with a window view of trees and blue sky, with those collected in a no-window one. Results showed that creative fluency was significantly greater in the nature-view scenario compared to the no-window scenario. Similar results were obtained by Mostajeran et al. [58], who examined the effects of the absence or presence of virtual plants on users' creativity in an office IVE. Indeed, the average creativity ratings obtained with the alternative uses task were significantly higher for the scenario with plants. Finally, participants in Yin et al. [56] performed cognitive tests by using a virtual desktop in VR inside three versions of biophilic open and enclosed virtual office spaces (i.e., natural elements, natural analogues, and combined scenarios) and a non-biophilic one. Compared to the base case, participants in biophilic scenarios showed higher creativity scores, and the creativity effects were significant and more prominent in enclosed spaces than in open ones.
- **Comprehension.** Cha et al. [75] conducted a *reading comprehension task* in four different virtual environments by manipulating ceiling height and type (i.e., open or concealed). However, non-statistically significant differences were found in reading speed, response time, and quiz score.

3.4.3. Physiological parameters

The results collected on the physiological responses of individuals in IBE are quite fragmented in relation to the type of parameter measured and the biophilic patterns investigated, as follows:

- **Heart rate (HR) and heart rate variability (HRV).** The improvement in HR and HRV were detected in only few IBE studies. Mihara et al. [60] found such improvements in interior spaces with larger windows, while in the experiment of Tan et al. [72] the same effect was measured after visual exposure to complex fractals in interior spaces. In two experiments Yin et al. [45,56] also detected positive changes in HR and HRV after exposure to office settings with different combinations of biophilic patterns (i.e., various natural elements and natural analogues in open spaces, and indoor green and outdoor view conditions). However, Li et al. [65] identified a sort of limit in the quantity of greenery beyond which biophilia benefits no longer manifest, showing that the improvement of HR was most pronounced with a moderate dose of greenery (i.e., green coverage ratio less than 80 %) in vegetable wall. In the remaining reviewed studies (7 of the 12 studies assessing HR/HRV) non-significant changes were observed for HR and HRV between biophilic and non-biophilic indoor environments.
- **Electrodermal activity (EDA) or Skin Conductance (SC).** Most studies that measured these parameters recorded physiological improvements, indicating a general stress reduction in the IBE scenario. For example, for Zeng et al. [67], according to the changes in SC level before and after participants experienced VR scenarios, the best design characteristics for a care facility were the presence of medium-height windows, warm colour of the space and curved upward raised ceiling, which can be features aligned with biophilic principles. Additionally, skin parameters were positively influenced in indoor spaces with a clear sky view and low sun angle compared to an overcast sky [49], when participants observed a view close to windows [47], as the level of indoor wood application increased [69], and when complex fractals were present on wall panels [72]. Yin et al. [44] further demonstrated the calming effects of including various natural elements in indoor spaces based on the recorded decrease of SC level. Interesting results were obtained by Yeom et al. [61] in which smaller green wall scenario compared to a non-biophilic scenario provided a lower SC value, resulting in reduced stress, while a larger green wall scenario provided a higher SC value indicating a higher stress level.

Similarly, the improvement of SC levels in IBEs in the experiment of Li et al. [65] was significantly better when green coverage ratio was below 80 %. Conversely, no impact of BD on measured skin parameters was observed by only 4 of the reviewed studies [45,56,63,65].

- **Skin Temperature (ST).** In the experiment by Sedghikhanshir et al. [64], the thermal state of 40 participants was compared in two virtual settings: a room with a green wall and the same room without biophilic elements, inside a climate chamber under a slightly warm condition (28.89 °C and 50 % relative humidity). No significant difference in the mean ST was found between scenarios. Similarly, in terms of local ST, no difference was observed for measurements at the neck or scapula, while only hand temperature was significantly higher in the biophilic scenario. Instead, in the study of Kim et al. [69], ST related to participant's subjective thermal sensation, increased as the indoor wood application level increased.
- **Blood Pressure (BP).** In both studies that measured this parameter, biophilic interventions were consistently associated with more decreasing BP compared to the non-biophilic environments, demonstrating the stress-relieving benefits of incorporating natural elements and natural analogues in office and school settings [44,56].
- **Electroencephalography (EEG).** Several experiments have recorded positive effect of IBE on brain wave activity. In the study of Kim et al. [78], Beta power measurements revealed significant improvements in visual-spatial information processing and visual attention in two biophilic classrooms (green wall and wood floor and green plant on one wall). Conversely, a non-significant difference in relative Alpha power spectrum was found between biophilic and non-biophilic environments. However, in other experiments, such as those by Lei et al. [63] and Yeom et al. [61] biophilic settings with moderate greenery coverage significantly increased the total power of the Alpha wave, showing a higher relaxing effect on the subjects, respectively when participants were subjected to a 20 % green coverage ratio virtual scenario, and in a small green wall scenario. Finally, Jung et al. [66] demonstrated that BD interventions (i.e., green wall and prospective space filled with nature) in hospital patient rooms not only increased Alpha activity, indicative of a relaxed state, but also reduced Beta activity, associated with heightened arousal, suggesting the reduction of tension.

3.4.4. Psychological aspects

As specified in Section 3.3.4, in order to meet the complexity of human feelings, all psychological questionnaires reported more than one outcome measure, each capturing a different emotion or affective response. BD might strongly affect certain emotions while having no impact on others. This section illustrates the psychological impacts of the IBEs, distinguishing between the effect on positive and negative emotions and the potential on stress recovery, as follows:

- The improvement of **emotions** due to BD interventions have been recorded by the majority of the 16 reviewed studies addressing the psychological state. **Positive affect** significantly increased in various settings, including a biophilic hospital room with a green wall and an anamorphic wall [66], office environments with greenery [58,62] and in a nature-view scenario compared to a non-window control scenario [51]. In addition**,** IBE results showed that participants in greenery indoor spaces experienced less dullness compared to scenarios without greenery [60], while high ceiling evokes emotions of happiness and curiosity [75], and proximity to a window led to higher pleasantness and arousal [47]. In line with these findings, in Yin et al. [44], participants in classroom with various natural elements reported lower frustration levels, and higher engagement and excitement levels compared to their responses in the non-biophilic environment.

Conversely, even if sometime reviewed studies reordered also a significantly decrease in **negative emotions** in IBE, with large natural outdoor view [66,77] or the presence of a green wall [62,66], other times BD didn't affect negative feeling. For example, the item "anger" did not appear to be an emotion related to the Prospect pattern [48], the "anxiety" score [65] and the level of "fear" and "sadness" [58] didn't change in presence of greenery. In addition, Yeom et al. [62] discovered also that the negative affect increased in the full-sized green wall and decreased in the one freestanding green wall scenario compared to the baseline, consistently with the mixed results on physiological parameters discussed in Section 3.4.2. Another mixed result was obtained by Zeng et al. [67], who discovered a design combination of medium height side windows and orange warm space interface enhanced the total emotional score, but also with the presence of an enclosed partition which can limit a quality Prospect condition.

- Concerning the evaluation of the hypothesis that mental recovery from **stress and anxiety** would be greater after exposure to biophilic environments, a clear distinction is evident between the results obtained using the well-know STAI questionnaire and those derived from self-designed survey. None of the studies investigating stress recovery with self-designed stress questions revealed significant differences between biophilic and non-biophilic scenarios [44,47,60]. Instead, in Yeom et al. [61], the STAI score was lower both in small green wall and large green wall scenarios than that in the non-green wall scenario. In addition, the STAI score in the small green wall scenario was significantly lower than that in the large green wall scenario, consistent with physiological findings discussed in Section 3.4.2. Similarly, in a hospital environment, STAI results showed that BD can decrease the anxiety state [66]. For Yin et al. [45], the "*outdoor view*" and "*combination*" scenarios entailed a greater decrease in STAI score compared with the non-biophilic environment. However, for this last study, the decrease of STAI was close to the null and not statistically significant, between the "*indoor green*" scenario and the non-biophilic environment, leading to inconsistent results.

4. Discussion

Based on the findings described in Section 3, the Paragraph 4.1 critically discusses the core characteristics (outlined in section 3.2) and experimental methods of the studies (reviewed in Section 3.3), as well as the key outcomes on the impacts of BD strategies on the dependent variable (as reported in section 3.4). The directions for future biophilic research efforts using IVEs are then presented in Paragraph 4.2, which reflects considerations drawn on research approaches in terms of biophilic patterns experimentation, dependent variables investigation and methods standardization to draw and extrapolate new results and impacts of BD strategies on human-dimension via VR.

4.1. Key observations

4.1.1. Characteristics and methods of experiments

Fig. 8 provides a graphical overview of the main biophilic patterns investigated by the analysed studies (i.e. independent variables in the left-hand side of the figure), in relation to the dependent variables' domains (right-hand side of the figure), also according to the VR technology used (in the middle of the figure). The key outcomes are discussed in the following points.

- The **investigated BD patterns** in the reviewed studies reveal a variegated range of independent variables. In particular, a clear predominance of "Visual Connection with Nature" and "Prospect" was detected. This is closely associated to the capacity of VR to effectively manipulate the visual domain, creating virtual nature-related stimuli while fully immersing and isolating users from their real-world surroundings. In addition, the relevant evaluation of these patterns in the current body of research may be influenced by their significant implementation and presence in real-world settings (i.e., integration of greeneries and presence of views out of windows). This suggests a correspondence between the actual application of BD strategies and their representation in the literature.
- In contrast to real-world scenarios, which tend to investigate individual BD patterns in isolation [12], IVEs studies present some but still limited attempts to explore multiple BD patterns in **multi-domain studies.** Real-world research is limited by the difficulty of testing multiple patterns simultaneously, whereas the flexibility of VR allows for more complex, and holistic experiences. Given the importance of investigating the multi-sensorial experience of humans within indoor environments to shape a beneficial human experience [13], VR technology presents a valuable opportunity for BD researchers to create an immersive biophilic experience and combine various stimuli and patterns. Indeed, reviewed studies highlighted the potential of IVEs to simulate diverse visual scenarios while also incorporating other sensory stimuli, such as, auditory [86], auditory and olfactory [52], auditory and thermal inputs [59].
- The effectiveness of VR investigation for BD research depends on the **type of VR technologies** used. Among the reviewed articles, head-mounted displays were the most common systems than the CAVEs. This is primarily due to their lower economic and computational cost while achieving a high level of realism as fully immersive systems.
- Despite the potential of VR technologies, ensuring the **validity of the experiments** is crucial for producing reliable and generalizable results, particularly in emerging research fields like BD. Some studies tried to enhance the VR validity by conducting preliminary validation studies, comparing results from IVE to their real counterparts and then using the virtual model as a provisional tool to assess different biophilic patterns. While this approach helps in confirming the reliability of VR simulations, it is not

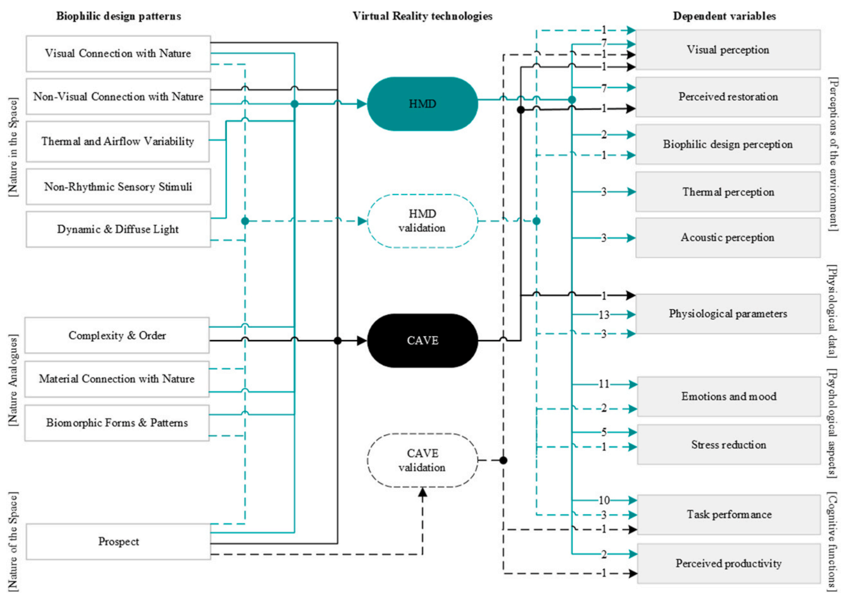

Fig. 8. Evidence map on the most frequent investigated biophilic design patterns (on the left) in relation to dependent variables (on the right), also according to the VR technology used (in the middle). The digits presented in the right-hand side of the figure inside the arrows represent the number of reviewed articles within the related topic.

always feasible given that it presupposes having a real test environment with biophilic settings, thus partly limiting the advantages of VR in terms of speed and costs of carrying out the study. Moreover, it is crucial to address key elements such as content, internal, face, criterion, and ecological validity to ensure that virtual environments produce meaningful results. A notable concern occurred from this literature analysis is the limited attention given to ecological validity. This factor is crucial for ensuring an accurate representation of the indoor environment and a fully immersive experience and obtaining realistic and valid users' feedback and measures. However, more than half of the reviewed studies do not provide a measure of the participants' sense of presence and immersivity within IVE, nor of cybersickness symptoms. Even among studies that perform those evaluations, the adopted methods vary, ranging from the IPQ method to self-made questionnaires, resulting in a lack of consistency in the assessment of the sense of presence.

- An additional challenge to ensure realistic feedback and the ecological validity of the virtual environment is maintaining participant **immersion** during IVE experiments. Often, subjective evaluations are administered using self-reporting questionnaires and interviews after the conclusion of the virtual experience. This post-experience approach can be intrusive and may disrupt immersion, leading to disorientation and potentially biased responses. Integrating tasks and surveys within the model directly in VR may reduce the break-in presence and avoid biases [25,93]. Nevertheless, only 27 % of the articles that involve the administration of a questionnaire explicitly state that they carry it out in an immersive environment. Ultimately, a comprehensive assessment of the sense of presence and cybersickness, as well as the administration of questionnaires during the virtual immersion could already be sufficient and effective actions in support of the ecological validity of the study.
- This issue supports another challenge identified by this review: **the lack of homogeneity in design of experiment**, leading to missing data or scarcity of information that pertains not only to ecological validity but also the methods, sample size, IVE exposure and indoor environmental assessment. Concerning the former, the experiment design varied, in relevance order, among repeated-measure design, independent-measure design, and mixed design. The number of participants to be tested (i.e., sample size) is also diversified, ranging between 15 and 256 subjects, with the majority of studies (65 %) analysing between 20 and 60 subjects and sometimes lacking the analysis of the statistical significance of the sample. Similarly, the immersion time in the virtual environment significantly varies across the studies, even if in most cases it appears rather limited (under 20 min), satisfying the need for limiting VR time exposure to avoid the occurrence of participants' disturbances which could invalidate the results. Moreover, most of the studies (52 %) excluded information on the environmental conditions of the real room where the experiment was conducted. However, Indoor Environmental Quality factors are essential and need to be controlled to mitigate their impact on the dependent variables, particularly linked to individuals psychological and physiological responses [61].
- Within the reviewed studies, a **wide range of dependent variables** have been investigated, demonstrating the interest in evaluating the benefits of BD covering the whole human dimension. These variables ranged primarily from individuals' perception and the related restoration potential (68 % of studies) followed by psychological aspects, such as emotion and stress (52 %) and physiological parameters, especially HR/HRV and EDA/SC (52 %). A minority, but still significant part (45 %) measures cognitive functions, especially attention and memory. Obviously, the fields of investigation very often overlap within the 74 % of studies, for example firstly evaluating the restoration theory and then the psychological aspects, or those addressing cognitive functions and physiological parameters.
- However, there is a noticeable **lack of standardization in methods for collecting dependent variables.** Indeed, the challenge lies in the fragmented and non-uniform nature of those methods. This is the results of extensive literature and different research field like psychology, neuroscience, and architecture, which have developed their own methods (i.e., questionnaires and tests) to investigate the human dimension. Moreover, as scientific understanding of human-environment interactions evolves, researchers continuously refine existing tools, or create newer self-made ones, to address the complexity and multi-dimensional nature of human perception more accurately. This development has led to multiple overlapping, yet distinct, methods for collecting dependent variables. This issue leads to difficulties in comparing results across BD studies, as the same dependent variables may be investigated by different or slightly different methods or use varying scales, leading to inconsistent and not fully comparable findings.

4.1.2. Impact of BD strategies

The key observations based on the evidence of the reviewed papers can be distinguished into two main categories: impact of BD strategies on perception and impacts related to the biophilic theories ART (perceived restoration and cognitive functions) and SRT (physiological and psychological aspects).

On one hand the positive impact of BD on **environmental perception** is evident across the reviewed studies. This is especially true concerning visual and spatial perception. Clear improvements in the presence of natural patterns, such as façade geometry, higher open spaces, higher view quality, larger window-to-wall ratios, were reported contributing to enhance user satisfaction in terms of visual appraisal [49,54,57,73], spaciousness [76], attractiveness [75], and overall perception of the BD design [44,56]. There are also some contradictory findings correlating higher green density to a weaker restorative response [63]. Interestingly, a negative impact on perceived privacy was detected in terms of large openings or open spaces [57,73,76]. However, BD influence on thermal and acoustic perception remains less consistent and quite contrasting. Indeed, the perceived thermal benefits of BD seemed to depend on the specific biophilic pattern simulated. For instance, a greater quantity of wood correlates with an increased sense of warmth [69], the presence of a green wall with an improvement in comfort but not in sensation [64], and different ratio of greenery can also induce no thermal effects [60]. The acoustic satisfaction under visual stimuli exposure was more improved by the quality of greenery, especially its richness, colours and variety of species [53,54], rather than its quantity, which was associated with higher noise annoyance [53] or no impact at all [60]. In general, these findings suggest that while BD is generally beneficial to visual perception, further research is needed to fully understand its impact on thermal and acoustic perceptions.

On the other hand, significant heterogeneity was observed also on findings associated with **BD theories** presented in the Introduction section. The benefits of BD in relation to Attention Restoration Theory and Stress Reduction Theory are evident across several studies, though results are somewhat varied.

The general premise of **Attention Recovery Theory** [10] is supported in terms of perceived restoration, with restorative experiences improved thanks to the inclusion of natural materials, like wood [70], greenery [58,79], and the proximity to natural views [40,47]. The reviewed studies provide only partial support to the idea that exposure to nature can improve cognitive functions with more pronounced improvements in certain cognitive domains than others, like mental flexibility and comprehension. While some studies reported improvements in attention and working memory in biophilic environments, the findings are inconsistent. Indeed, only a few studies reported significant benefits from visual [44,58,63,86,92] and audio-visual [86] connection with nature, while others found a decrease in performance [56] or no significant differences [44,62], even in the case of window views and daylight [46,51] or room curved contours design [71]. However, creativity consistently benefited from biophilic exposure across multiple studies, indicating that natural analogues [56], natural elements [56,58] and window view [51] can enhance creative thinking.

According to health-related theories, psychophysiological responses to natural settings are emphasized by the **Stress Reduction Theory** [11]. Among the reviewed studies, the **physiological impacts of BD** are fragmented depending on the type of parameters measured, the biophilic patterns tested and related quantity. Electrodermal Activity (EDA) or Skin Conductance (SC) and Blood Pressure (BP) emerged as particularly sensitive measures to BD strategies affirming its stress-relieving effects in the presence of Nature in the Space and Analogues [44,47,49,56,67,69,72]. Heart Rate (HR) and Heart Rate Variability (HRV) were frequently measured in studies but showed a more limited stress reduction influence [45,56,60,65,72]. Skin temperature (ST) results were also inconsistent [64], with only some biophilic interventions like wood application increasing localized temperature [69] improving thermal comfort during the heating season. Electroencephalography (EEG) results have also demonstrated an improved relaxation and reduced tension thanks to an increased Alpha wave activity and reduced Beta activity in biophilic spaces [61,63,66,78]. It is essential to point out that if the sensitivity of measurement tools is not appropriate, partial or inconsistent improvements in stress recovery can be detected. Despite the variability in results, these findings highlight the potential of BD to positively influence physiological responses reducing stress levels and supporting SRT under specific conditions.

Due to the complexity of human feelings, the **psychological impacts of BD** reveal mixed effects on emotional states across the reviewed studies depending on the investigated emotional dimension. Regardless of patterns and settings, positive emotions (e.g., happy, engagement, excitement, inspiration, interest, enthusiasm, energy, joy) were generally enhanced through BD interventions, with significant increases in affective responses recorded in environments with greenery [58,62,66], natural views and higher ceilings [47,51,60,75]. Conversely, the effect of BD on the reduction of negative emotions was less consistent. While some studies reported a decrease in negative feelings such as anxiety and frustration [44,46,66,77], others found no significant impact on emotions like anger, fear, or sadness in the presence of greenery [58,65] and prospect [48]. In some cases, the presence of full-sized green wall scenario compared to smaller green wall configurations even led to an increase in negative affect [62]. This result aligns with the physiological outcomes and highlights that an oversized quantity of greenery may have negative impacts on individuals. Lastly, the results concerning stress and anxiety recovery varied depending on the experimental methods. Indeed, studies using standardized measures (i.e., STAI questionnaire) found that biophilic environments could reduce stress and anxiety levels, particularly in spaces with green walls [61,66] or view of nature [45]. However, self-designed surveys showed no significant influence [44,47,60], thus emphasizing the need for standardized tools to measure the psychological benefits of BD.

To conclude, despite the overall potential for BD to enhance restoration and reduce stress under specific conditions is clear, supporting both ART and SRT, the picture drawn so far highlights the need to carefully weigh the design when defining biophilic strategies to maximise benefits across all aspects without compromising others.

The investigated literature generally provides support, although not totally unanimous, to the idea of a positive occupants' response to various indoor biophilic scenarios in terms of perceptions, cognitive functions, emotion, mood, stress or alertness. The picture of the results obtained appears however quite fragmented, consistently with results of research conducted in real-world settings. Indeed, it is common to find a partial positive impact of BD also in the studies carried out in "physical" spaces (i.e., real-world settings) [12,15,94,95].

4.2. Future research directions

The considerations drawn so far lead to the definition of several research perspectives strongly linked to the VR potential to advance BD studies.

First of all, the body of knowledge on the benefits of BD should be extended by **analysing a broader range of biophilic patterns across various sensory dimensions** (visual, auditory, olfactory). In this context, conducting multi-domain experiments in real settings presents challenges due to limitations in the environmental settings that researchers can control at once [25]. This limitation may not fully capture the multisensory richness of biophilic environments. VR offers a solution to this dilemma by providing a controllable and adaptable environment, allowing researchers to contemporary test a wide range of patterns. Indeed, the advantage of VR to easily deliver several, multi-sensory realistic and fully immersive visual and acoustic stimuli in a randomized manner and allows for testing a greater number of independent variables at minimal expense. Despite that, this proven benefit still potential still needs to be widely exploited even this approach would support researchers to assess how specific or combined natural elements affect occupants' dimensions, especially in specific sensitive contexts (e.g. hospitals).

Secondly, the evaluation of the impact of BD strategies should also be more often and simultaneously extended to **investigate a**

wider range of dependent variables related to humans' well-being and health. VR is particularly well-suited for this task, as specific questionnaires on psychology and perception, as well as cognitive tasks, can be easily implemented, while simultaneously measuring the environmental and subjects' physiological parameters. An important point to keep always in mind when designing studies aimed at evaluating the impact of multiple BD patterns on different dependent variables, it is crucial to account for limitations on exposure time within the virtual environment. Additionally, the integration of further means of study could support the collection of a wider range of dependent variable and enhance the comprehension of data collection. In this context, eye-tracking technology can be adopted to get insights on processing tasks and allocation of attention and/or distraction in simulated environments with biophilic indoor elements [56,63,96]. Indeed, HMD equipped with eye-tracking is a valuable tool in VR-based research offering the opportunity to continuously monitor individuals' eye behaviour without disrupting users' immersivity.

Thirdly, the impact of BD strategies may vary among different indoor settings (e.g. residences, schools, workplaces, hospitals …) and some biophilic strategies may be more suitable in some contexts than others [13]. As a result, **investigating BD benefits in various scenarios and environments** is essential to fully understand the effectiveness of biophilic interventions. This is especially feasible by using VR systems given the flexibility of representing different contexts.

Lastly, to effectively support the extension of Biophilic Design research in VR, the most ambitious research perspective is the need to **develop a comprehensive experimental framework**. By supporting researchers to conduct rigorous test sessions and gathering reliable data, this framework has the potential to facilitate the simultaneous collection of multiple aspects (i.e., dependent variable). Such approach would address the current fragmentation and heterogeneity of existing literature, as highlighted in this review. Consequently, the standardization of tests, methods and design of experiments would allow to create a more cohesive body of knowledge in the field and produce comparable results across different studies. This would allow to establish and quantify the actual BD benefits. Additionally, it would support the integration of VR findings into evidence-based building design, building standards and certifications. The present literature review constitutes an initial step toward this valuable objective, providing a critical analysis of existing studies and paving the way for the development of innovative methodologies and future research phases.

5. Conclusions

In conclusion, this review aimed to bridge the literature gap on the application of fully Immersive Virtual Environments in indoor Biophilic Design research. Indeed, despite the growing body of research, the existing literature is not numerically extended and remains highly fragmented, lacking systematic synthesis, especially concerning the outcomes of BD on human dimensions. As a result, this work reflects a double-fold objective. On one side, to provide a comprehensive overview of current studies, exploring studies characteristics, related to investigated BD patterns, VR technologies, test design, and methods adopted to collect dependent variables concerning individuals' perception, cognition and psychophysiology. On the other, to synthesize the key observation, offering a structured foundation for future research. Indeed, a strong emphasis is placed on the identification of BD impact on human dimensions as detected in IVE studies.

By analysing a body of 31 articles that adopted fully IVE, the review has highlighted the potential of VR application to advance BD research by offering an affordable alternative or complementing, traditional laboratory and real-site approaches for investigating the «human dimension» in buildings. VR provides the creation of adaptable environments, allowing researchers to easily replicate and manipulate biophilic settings and contemporary test a wide range of patterns at once, which can lead to more robust and diverse findings. This is a crucial point to fully capture the multisensory richness of biophilic environments. In the future, immersive virtual environments will be used more and more often for research on the impact of interior design on humans.

However, the review highlights the fragmented nature of current research, which often varies in terms of experimental design, methods, and dependent variables. Thus, the manuscript underscores the challenges of standardizing research methods in this emerging field and emphasizes the need for more holistic and ecologically valid approaches to fully leverage VR technology's capabilities in BD research on individuals.

By synthesizing the key observations from results on perception, physiological, psychological, and cognitive aspects, this review provides valuable insights into the potential of VR-BD studies to enhance human experience in built environments. Indeed, the review finds positive impacts of BD on visual and spatial perception, though its effects on thermal and acoustic perception are less consistent depending on specific BD patterns. The results of VR-based studies support Attention Restoration and Stress Reduction Theories with improved restoration and stress reduction, but the evidence on cognitive functions is mixed. Physiological responses, such as skin conductance and blood pressure consistently indicated positive effects, with heart rate and skin temperature responses being less conclusive. Lastly, positive emotions were generally enhanced, though BD effect on reducing negative emotions is inconsistent. Overall, the findings are inhomogeneous, highlighting the need for carefully designed strategies.

As a result, expanding the knowledge in this field brings advantages for building designers but also for the improvement of buildings' rating protocols and certifications in terms of social sustainability, well-being and health of the occupants.

CRediT authorship contribution statement

Elisa Di Giuseppe: Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Ludovica Marcelli:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Arianna Latini:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Marco D'Orazio:** Funding acquisition.

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.

Appendix A

Table A.1
Data on the methodology design of the eligible studies. V = Visual connection with nature, NV = Non-Visual connection with nature, TA = Thermal & Airflow variability, L = Dynamic & diffuse Light category, NRS = Non-Rhythmic Sensory stimuli, M = Material connection with nature, FP = Biomorphic Forms & Patterns, CO = Complexity & Order, P = Prospect; HMD = virtual environment using Head-mounted display, CAVE = Cave Automatic Virtual Environment; M = virtual modelled experience, R = virtual recorded experience; real = real environment, 2D = non immersive virtual environment (i.e., computer display condition); IPQ = immersion/sense of presence/realism questionnaire, SSQ = simulator sickness questionnaire (*self-made questions); Single = single-domain, Multi = multi-domain, Cross = crossed effect; W = within-subjects design, B = between-subjects design; CS = case study; nr = no time restrictions; T° = temperature, RH = relative humidity, CO_2 = carbon dioxide concentrations, $PM_{2.5}$ = $PM_{2.5}$ concentrations, LUX = light intensity, AV = air velocity.

Studies characteristics																										
Ref.	Environment	Nature in the space					Natural analogues			Nature of the space	Devices	Virtual experience	IBE Validation	Ecological validity		Domain	Design		Sample size	Exposure time	Monitored parameters					
		V	NV	TA	L	NRS	M	FP	CO	P				IPQ	SSQ		W	B			T°	RH	CO_2	$PM_{2.5}$	LUX	AV
[68]	Office	✓			✓					✓	HMD	M	✓ (real vs HMD)	✓*		Single	✓		112	-					✓	
[44]	School	✓					✓			✓	HMD	R	✓ (real vs HMD)			Single	✓		28	5 min						
[56]	Office	✓			✓		✓	✓		✓	HMD	M				Single	✓		30	10 min	✓	✓		✓		
[75]	Office									✓	HMD	M		✓		Single	✓		40	7 min						
[57]	Office	✓								✓	HMD	M	✓ (real vs HMD)	✓		Single	✓		50	5 min						
[45]	Office	✓			✓		✓	✓		✓	HMD	M				Single		✓	100	6 min	✓	✓	✓	✓		
[77]	School	✓								✓	HMD	M	✓ (real vs HMD)	✓		Single	✓		35	5 min						
[47]	Office	✓								✓	HMD	R			✓	Single	✓		32	10 min	✓	✓			✓	
[48]	Office	✓								✓	HMD	M				Single	✓		37	2 min					✓	
[61]	Office	✓									HMD	M				Single	✓		27	6 min	✓	✓	✓		✓	
[71]	Home							✓			HMD	M		✓	✓	Single	✓		42	12 min						
[62]	Office	✓									HMD	M		✓		Single	✓		27	8 min	✓	✓				
[63]	Office	✓									HMD	M				Single	✓		15	20 min	✓					
[49]	Office	✓			✓				✓	✓	HMD	M				Single	✓	✓	256	nr	✓	✓			✓	
[64]	Other	✓									HMD	M		✓	✓	Cross	✓		40	10 min	✓	✓				
[78]	School	✓					✓	✓			HMD	M	✓ (2D vs HMD)			Single	✓		17	30 sec						
[51]	Office	✓			✓					✓	HMD	M				Single	✓		CS 1: 54 CS 2: 57	-						
[65]	Other	✓									HMD	R				Single	✓	✓	CS 1: 31 CS 2: 62	6 min	✓	✓	✓			
[40]	School	✓	✓							✓	CAVE	R				Multi		✓	88	6 min	✓	✓				
[54]	Office	✓								✓	HMD	M				Cross	✓		34	nr						
[58]	Office	✓									HMD	M		✓	✓	Single	✓		39	12 min						
[69]	Home						✓				HMD	M		✓		Cross	✓		26	3 min	✓	✓	✓			✓
[79]	School	✓	✓	✓	✓		✓			✓	HMD	M				Multi	✓		52	10 min						
[53]	Home	✓							✓	✓	HMD	M		✓*		Cross	✓		CS 1: 79 CS 2: 62	5 min						
[60]	Other	✓								✓	HMD	M			✓	Cross	✓		90	2 min	✓	✓			✓	
[74]	Office									✓	CAVE	M	✓ (2D vs CAVE)		✓*	Single		✓	57	nr						
[66]	Hospital	✓								✓	HMD	M				Single		✓	75	2 min						
[67]	Hospital	✓			✓					✓	HMD	M		✓*		Single	✓	✓	90	5 min						
[70]	School						✓				HMD	M				Single	✓		35	nr						
[72]	Office								✓		CAVE	M				Single	✓		45	1,5 min						
[80]	Office	✓	✓								HMD	M		✓	✓	Multi	✓	✓	198	6 min	✓					✓

Table A.2
Information on methods for collection of dependent variables: perceptions domain investigated (i.e., visual perception, perceived restoration, perception of biophilic design, thermal and acoustic perception); physiological parameters measured (HR = heart rate, BP = blood pressure, SC = skin conductance activity or EDA = electrodermal activity, ST = skin temperature, EEG = electroencephalography); psychological aspects investigated; methods to evaluate cognitive performance and load.

Ref.	Year	Collected dependent variables: Perceptions domain investigated					Physiological parameters					Psychological aspects		Cognitive evaluation	
		Visual	Restoration	Biophilia	Thermal	Acoustic	HR	BP	SC/ EDA	ST	EEG	Emotion	Stress	Task performance	Self-reported cognitive load
[68]	2015													✓	
[44]	2018			✓			✓	✓	✓			✓	✓	✓	
[56]	2019			✓			✓	✓	✓				✓	✓	
[75]	2019	✓										✓		✓	
[57]	2019	✓													
[45]	2020						✓	✓	✓						
[77]	2020						✓					✓		✓	
[47]	2020		✓				✓		✓			✓	✓		
[48]	2020	✓							✓			✓			
[61]	2021						✓				✓		✓		
[71]	2021	✓	✓									✓		✓	
[62]	2021											✓		✓	✓
[63]	2021		✓				✓		✓		✓			✓	
[49]	2022	✓					✓		✓						
[64]	2022				✓		✓			✓					
[78]	2022										✓				
[51]	2022											✓		✓	
[65]	2022						✓		✓			✓			
[40]	2022		✓												
[54]	2022	✓				✓								✓	
[58]	2023		✓									✓		✓	
[69]	2023				✓				✓	✓	✓				
[79]	2023	✓	✓											✓	
[53]	2023			✓		✓									
[60]	2023	✓			✓	✓	✓					✓	✓		✓
[74]	2023	✓												✓	✓
[66]	2023										✓	✓	✓		
[67]	2023		✓						✓			✓			
[70]	2023		✓												
[72]	2024	✓					✓		✓						
[80]	2024													✓	

Data availability

Data will be made available on request.

References

[1] WorldGBC, health & wellbeing framework: six principles for a healthy, sustainable built environment, Exec. Rep. (2020) 18. https://worldgbc.org/sites/default/files/WorldGBCHealth%26WellbeingFramework_ExecReport_FINAL.pdf.

[2] World Green Building Council, Building the business case: health, wellbeing and productivity in green offices, better places for people campaign, 27, http://www.worldgbc.org/sites/default/files/WGBC_BtBC_Dec2016_Digital_Low-MAY24_0.pdf, 2016.

[3] European Ventilation Industry Association, Evia's Eu Manifesto: Good Indoor Air Quality Is a Basic Human Right, 2019.

[4] European Commission, Indoor air pollution: new EU research reveals higher risks than previously thought. https://ec.europa.eu/commission/presscorner/detail/en/IP_03_1278, 2003.

[5] S.R. Kellert, J. Heerwagen, M. Mador, Biophilic Design : the Theory, Science, and Practice of Bringing Buildings to Life, 2008.

[6] Stephen R. Kellert, Nature by Design: the Practice of Biophilic Design, Yale University Press, 2018.

[7] N. Wijesooriya, A. Brambilla, Bridging biophilic design and environmentally sustainable design: a critical review, J. Clean. Prod. 283 (2021) 124591, https://doi.org/10.1016/j.jclepro.2020.124591.

[8] W.D. Browning, C.O. Ryan, J.O. Clancy, 14 Patterns ofBiophilic Design: improving health & wellbeing in the built environment, Terrapin Bright Green 1 (2014) 1–64.

[9] S. Kaplan, The restorative benefits of nature: toward an integrative framework, J. Environ. Psychol. 15 (1995) 169–182, https://doi.org/10.1016/0272-4944(95)90001-2.

[10] S. Kaplan, The restorative environment: nature and human experience, in: D. Relf (Ed.), The Role of Horticulture in Human Well Being and Social Development, Timber Press, 1992, pp. 134–142.

[11] R.S. Ulrich, R.F. Simonst, B.D. Lositot, E. Fioritot, M.A. Milest, M. Zelsont, Stress Recovery during Exposure to Natural and Urban Environments, 1991.

[12] K. Gillis, B. Gatersleben, A review of psychological literature on the health and wellbeing benefits of biophilic design, Buildings 5 (2015) 948–963, https://doi.org/10.3390/buildings5030948.

[13] T. Peters, K.D. Penna, Biophilic design for restorative university learning environments : a critical review of literature and design recommendations, Sustainability (Switzerland) 12 (2020) 7064, https://doi.org/10.3390/su12177064.
[14] A. Sal Moslehian, P.B. Roös, J.S. Gaekwad, L. Van Galen, Potential risks and beneficial impacts of using indoor plants in the biophilic design of healthcare facilities: a scoping review, Build. Environ. 233 (2023), https://doi.org/10.1016/j.buildenv.2023.110057.
[15] T.A. Norton, O.B. Ayoko, N.M. Ashkanasy, A socio-technical perspective on the application of green ergonomics to open-plan offices: a review of the literature and recommendations for future research, Sustainability (Switzerland) 13 (2021), https://doi.org/10.3390/su13158236.
[16] Y. Zhang, H. Liu, S.C. Kang, M. Al-Hussein, Virtual reality applications for the built environment: research trends and opportunities, Autom. ConStruct. 118 (2020), https://doi.org/10.1016/j.autcon.2020.103311.
[17] L. Maffei, M. Masullo, A. Pascale, G. Ruggiero, V.P. Romero, Immersive virtual reality in community planning: acoustic and visual congruence of simulated vs real world, Sustain. Cities Soc. 27 (2016) 338–345, https://doi.org/10.1016/j.scs.2016.06.022.
[18] L. Maffei, M. Masullo, A. Pascale, G. Ruggiero, V. Puyana Romero, On the validity of immersive virtual reality as tool for multisensory evaluation of urban spaces, Energy Proc. 78 (2015) 471–476, https://doi.org/10.1016/j.egypro.2015.11.703.
[19] A. Latini, E. Di Giuseppe, M.D. Orazio, Development and application of an experimental framework for the use of virtual reality to assess building users ' productivity, J. Build. Eng. 70 (2023) 106280, https://doi.org/10.1016/j.jobe.2023.106280.
[20] H. Alamirah, M. Schweiker, E. Azar, Immersive virtual environments for occupant comfort and adaptive behavior research – a comprehensive review of tools and applications, Build. Environ. 207 (2021) 108396, https://doi.org/10.1016/j.buildenv.2021.108396.
[21] J.M. Davila Delgado, L. Oyedele, P. Demian, T. Beach, A research agenda for augmented and virtual reality in architecture, engineering and construction, Adv. Eng. Inf. 45 (2020) 101122, https://doi.org/10.1016/j.aei.2020.101122.
[22] Y. Zhang, H. Liu, S.C. Kang, M. Al-Hussein, Virtual reality applications for the built environment: research trends and opportunities, Autom. ConStruct. 118 (2020) 103311, https://doi.org/10.1016/j.autcon.2020.103311.
[23] A. Latini, E. Di Giuseppe, M. D'Orazio, Immersive virtual vs real office environments: a validation study for productivity, comfort and behavioural research, Build. Environ. (2023) 109996, https://doi.org/10.1016/J.BUILDENV.2023.109996.
[24] A. Latini, E. Di Giuseppe, M. D'Orazio, C. Di Perna, Exploring the use of immersive virtual reality to assess occupants' productivity and comfort in workplaces: an experimental study on the role of walls colour, Energy Build. 253 (2021) 111508, https://doi.org/10.1016/j.enbuild.2021.111508.
[25] H. Alamirah, M. Schweiker, E. Azar, Immersive virtual environments for occupant comfort and adaptive behavior research – a comprehensive review of tools and applications, Build. Environ. 207 (2022) 108396, https://doi.org/10.1016/j.buildenv.2021.108396.
[26] M.J. Liberatore, W.P. Wagner, Virtual, mixed, and augmented reality: a systematic review for immersive systems research, Virtual Real. 25 (2021) 773–799, https://doi.org/10.1007/s10055-020-00492-0.
[27] M. Mollazadeh, Y. Zhu, Application of virtual environments for biophilic design: a critical review, Buildings 11 (2021), https://doi.org/10.3390/buildings11040148.
[28] A. Latini, Immersive Virtual Reality for a Building Design: Defining, Validating and Applying an Innovative Framework, Springer Nature Switzerland, Cham, Switzerland, 2024, https://doi.org/10.1007/978-3-031-66028-3.
[29] M.F. Shiratuddin, W. Thabet, D.A. Bowman, D. Bowman, Evaluating the effectiveness of virtual environment displays for reviewing construction 3D models. https://www.researchgate.net/publication/228939426, 2004.
[30] K.-E. Bystrom, W. Barfield, C. Hendrix, A conceptual model of the sense of presence in virtual environments, Presence 8 (1999) 241–244, https://doi.org/10.1162/105474699566107.
[31] M. Slater, Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments, Phil. Trans. Biol. Sci. 364 (2009) 3549–3557, https://doi.org/10.1098/rstb.2009.0138.
[32] M. Slater, S. Wilbur, A Framework for Immersive Virtual Environments (FIVE): speculations on the Role of Presence in Virtual Environments Presence governs aspects of autonomie responses and higher-level behaviors of a participant in a VE. The paper considers single and multi-p, Presence 6 (1997) 603–616.
[33] M. V Sanchez-Vives, M. Slater, From presence to consciousness through virtual reality, Nat. Rev. Neurosci. 6 (2005) 332–339, https://doi.org/10.1038/nrn1651.
[34] J. Motejlek, E. Alpay, Taxonomy of virtual and augmented reality applications in education, IEEE Trans. Learn. Technol. 14 (2021) 415–429, https://doi.org/10.1109/TLT.2021.3092964.
[35] J.S. Gaekwad, A. Sal Moslehian, P.B. Roös, A meta-analysis of physiological stress responses to natural environments: biophilia and Stress Recovery Theory perspectives, J. Environ. Psychol. 90 (2023), https://doi.org/10.1016/j.jenvp.2023.102085.
[36] M.J. Grant, A. Booth, A typology of reviews: an analysis of 14 review types and associated methodologies, Health Inf. Libr. J. 26 (2009) 91–108, https://doi.org/10.1111/j.1471-1842.2009.00848.x.
[37] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman, T.P. Group, Preferred reporting items for systematic reviews and meta-analyses : the PRISMA statement, PLoS Med. 6 (1) (2009) 7, https://doi.org/10.1371/journal.pmed.1000097.
[38] M.J. Page, J.E. Mckenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, L. Shamseer, J.M. Tetzlaff, E.A. Akl, S.E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M.M. Lalu, T. Li, E.W. Loder, E. Mayo-wilson, S. Mcdonald, L.A. Mcguinness, L.A. Stewart, J. Thomas, A.C. Tricco, V.A. Welch, P. Whiting, D. Moher, The PRISMA 2020 statement : an updated guideline for reporting systematic reviews, Syst. Rev. (2021) 1–11.
[39] M. Gusenbauer, N.R. Haddaway, Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google Scholar, PubMed, and 26 other resources, Res. Synth. Methods 11 (2020) 181–217, https://doi.org/10.1002/jrsm.1378.
[40] S. Shin, M.H.E.M. Browning, A.M. Dzhambov, Window access to nature restores: a virtual reality experiment with greenspace views, sounds, and smells, Ecopsychology 14 (2022) 253–265, https://doi.org/10.1089/eco.2021.0032.
[41] A. Liberati, D.G. Altman, J. Tetzlaff, C. Mulrow, P.C. Gøtzsche, J.P.A. Ioannidis, M. Clarke, P.J. Devereaux, J. Kleijnen, D. Moher, The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration, J. Clin. Epidemiol. (2009) e1–e34, https://doi.org/10.1016/j.jclinepi.2009.06.006.
[42] S. Saeidi, Y. Zhu, J.-H. Choi, C. Zhong, Q. Wang, Immersive Virtual Environment as an Apparatus for Occupant Behavior Studies, 2016, pp. 11–13. ConVR2016.
[43] M. Afzal, R.Y.M. Li, M.F. Ayyub, M. Shoaib, M. Bilal, Towards BIM-based sustainable structural design optimization: a systematic review and industry perspective, Sustainability 15 (2023) 15117, https://doi.org/10.3390/su152015117.
[44] J. Yin, S. Zhu, P. MacNaughton, J.G. Allen, J.D. Spengler, Physiological and cognitive performance of exposure to biophilic indoor environment, Build. Environ. 132 (2018) 255–262, https://doi.org/10.1016/j.buildenv.2018.01.006.
[45] J. Yin, J. Yuan, N. Arfaei, P.J. Catalano, J.G. Allen, J.D. Spengler, Effects of biophilic indoor environment on stress and anxiety recovery: a between-subjects experiment in virtual reality, Environ. Int. 136 (2020) 105427, https://doi.org/10.1016/j.envint.2019.105427.
[46] A. Emamjomeh, Y. Zhu, M. Beck, The potential of applying immersive virtual environment to biophilic building design: a pilot study, J. Build. Eng. 32 (2020) 101481, https://doi.org/10.1016/j.jobe.2020.101481.
[47] F. Abd-Alhamid, M. Kent, J. Calautit, Y. Wu, Evaluating the impact of viewing location on view perception using a virtual environment, Build. Environ. 180 (2020) 106932, https://doi.org/10.1016/j.buildenv.2020.106932.
[48] S. Yeom, H. Kim, T. Hong, H.S. Park, D.E. Lee, An integrated psychological score for occupants based on their perception and emotional response according to the windows' outdoor view size, Build. Environ. 180 (2020), https://doi.org/10.1016/j.buildenv.2020.107019.
[49] K. Chamilothori, J. Wienold, C. Moscoso, B. Matusiak, M. Andersen, Subjective and physiological responses towards daylit spaces with contemporary façade patterns in virtual reality: influence of sky type, space function, and latitude, J. Environ. Psychol. 82 (2022), https://doi.org/10.1016/j.jenvp.2022.101839.
[50] N. Kim, J. Gero, Neurophysiological responses to biophilic design: a pilot experiment using VR and EEG biomimetic inspired architectural design view project design neurocognition view project, design computing and cognition, 1–21, https://www.researchgate.net/publication/359892380, 2022.
[51] L.A. Sharam, K.M. Mayer, O. Baumann, Design by nature : the influence of windows on cognitive performance and affect, J. Environ. Psychol. 85 (2023) 101923, https://doi.org/10.1016/j.jenvp.2022.101923.

[52] S. Shin, M.H.E.M. Browning, A.M. Dzhambov, Window access to nature restores: a virtual reality experiment with greenspace views, sounds, and smells, Ecopsychology 14 (2022) 253–265, https://doi.org/10.1089/eco.2021.0032.
[53] T. Van Renterghem, E. Vermandere, M. Lauwereys, Road traffic noise annoyance mitigation by green window view : optimizing green quantity and quality, Urban For. Urban Green. 88 (2023) 128072, https://doi.org/10.1016/j.ufug.2023.128072.
[54] J.Y. Jeon, H.I. Jo, B.B. Santika, H. Lee, Crossed effects of audio-visual environment on indoor soundscape perception for pleasant open-plan office environments, Build. Environ. 207 (2022), https://doi.org/10.1016/j.buildenv.2021.108512.
[55] A. Heydarian, J.P. Carneiro, D. Gerber, B. Becerik-Gerber, T. Hayes, W. Wood, Immersive virtual environments versus physical built environments: a benchmarking study for building design and user-built environment explorations, Autom. ConStruct. 54 (2015) 116–126, https://doi.org/10.1016/j.autcon.2015.03.020.
[56] J. Yin, N. Arfaei, P. MacNaughton, P.J. Catalano, J.G. Allen, J.D. Spengler, Effects of biophilic interventions in office on stress reaction and cognitive function: a randomized crossover study in virtual reality, Indoor Air 29 (2019) 1028–1039, https://doi.org/10.1111/ina.12593.
[57] T. Hong, M. Lee, S. Yeom, K. Jeong, Occupant responses on satisfaction with window size in physical and virtual built environments, Build. Environ. 166 (2019) 106409, https://doi.org/10.1016/J.BUILDENV.2019.106409.
[58] F. Mostajeran, F. Steinicke, S. Reinhart, W. Stuerzlinger, B.E. Riecke, S. Kühn, Adding virtual plants leads to higher cognitive performance and psychological well-being in virtual reality, Sci. Rep. 13 (2023), https://doi.org/10.1038/s41598-023-34718-3.
[59] A. Mahrous, K. Dewidar, M. Refaat, A. Nessim, The impact of biophilic attributes on university students level of Satisfaction: using virtual reality simulation, Ain Shams Eng. J. (2023) 102304, https://doi.org/10.1016/J.ASEJ.2023.102304.
[60] K. Mihara, D.J.C. Hii, H. Takasuna, K. Sakata, How does green coverage ratio and spaciousness affect self-reported performance and mood? Build. Environ. 245 (2023) 110939 https://doi.org/10.1016/j.buildenv.2023.110939.
[61] S. Yeom, H. Kim, T. Hong, Psychological and physiological effects of a green wall on occupants: a cross-over study in virtual reality, Build. Environ. 204 (2021) 108134, https://doi.org/10.1016/j.buildenv.2021.108134.
[62] S. Yeom, H. Kim, T. Hong, C. Ji, D.E. Lee, Emotional impact, task performance and task load of green walls exposure in a virtual environment, Indoor Air 32 (2022), https://doi.org/10.1111/ina.12936.
[63] Q. Lei, C. Yuan, S.S.Y. Lau, A quantitative study for indoor workplace biophilic design to improve health and productivity performance, J. Clean. Prod. 324 (2021) 129168, https://doi.org/10.1016/j.jclepro.2021.129168.
[64] A. Sedghikhanshir, Y. Zhu, Y. Chen, B. Harmon, Exploring the impact of green walls on occupant thermal state in immersive virtual environment, Sustainability (Switzerland) 14 (2022), https://doi.org/10.3390/su14031840.
[65] Z. Li, Y. Wang, H. Liu, H. Liu, Physiological and psychological effects of exposure to different types and numbers of biophilic vegetable walls in small spaces, Build. Environ. 225 (2022) 109645, https://doi.org/10.1016/j.buildenv.2022.109645.
[66] D. Jung, D.I. Kim, N. Kim, Bringing nature into hospital architecture: machine learning-based EEG analysis of the biophilia effect in virtual reality, J. Environ. Psychol. 89 (2023) 102033, https://doi.org/10.1016/J.JENVP.2023.102033.
[67] X. Zeng, P. Luo, T. Wang, H. Wang, X. Shen, Screening visual environment impact factors and the restorative effect of four visual environment components in large-space alternative care facilities, Build. Environ. 235 (2023) 110221, https://doi.org/10.1016/j.buildenv.2023.110221.
[68] A. Heydarian, J.P. Carneiro, D. Gerber, B. Becerik-Gerber, T. Hayes, W. Wood, Immersive virtual environments versus physical built environments: a benchmarking study for building design and user-built environment explorations, Autom. ConStruct. 54 (2015) 116–126, https://doi.org/10.1016/j.autcon.2015.03.020.
[69] S. Kim, B.Y. Yun, J.Y. Choi, Y.U. Kim, S. Kim, Quantification of visual thermal perception changes in a wooden interior environment using physiological responses and immersive virtual environment, Build. Environ. 240 (2023), https://doi.org/10.1016/j.buildenv.2023.110420.
[70] J. Li, S. Chen, H. Xu, J. Kang, Effects of implanted wood components on environmental restorative quality of indoor informal learning spaces in college, Build. Environ. 245 (2023), https://doi.org/10.1016/j.buildenv.2023.110890.
[71] N. Tawil, I.M. Sztuka, K. Pohlmann, S. Sudimac, S. Kühn, The living space: psychological well-being and mental health in response to interiors presented in virtual reality, Int. J. Environ. Res. Publ. Health 18 (2021), https://doi.org/10.3390/ijerph182312510.
[72] L. Tan, J. Wu, J. Kang, H. Xu, The visual preference and physiological response to Sierpinski triangle acoustic diffuser: an experimental study using VR technique, J. Environ. Psychol. 93 (2024) 102227, https://doi.org/10.1016/J.JENVP.2023.102227.
[73] S. Yeom, H. Kim, T. Hong, H.S. Park, D.E. Lee, An integrated psychological score for occupants based on their perception and emotional response according to the windows' outdoor view size, Build. Environ. 180 (2020), https://doi.org/10.1016/j.buildenv.2020.107019.
[74] M.O. Wong, Z. Zheng, H. Liang, J. Du, S. Zhou, S. Lee, How does VR differ from renderings in human perception of office layout design? A quantitative evaluation of a full-scale immersive VR, J. Environ. Psychol. 89 (2023), https://doi.org/10.1016/j.jenvp.2023.102043.
[75] S.H. Cha, C. Koo, T.W. Kim, T. Hong, Spatial perception of ceiling height and type variation in immersive virtual environments, Build. Environ. 163 (2019) 106285, https://doi.org/10.1016/j.buildenv.2019.106285.
[76] M.O. Wong, Z. Zheng, H. Liang, J. Du, S. Zhou, S. Lee, How does VR differ from renderings in human perception of office layout design? A quantitative evaluation of a full-scale immersive VR, J. Environ. Psychol. 89 (2023), https://doi.org/10.1016/j.jenvp.2023.102043.
[77] A. Emamjomeh, Y. Zhu, M. Beck, The potential of applying immersive virtual environment to biophilic building design: a pilot study, J. Build. Eng. 32 (2020), https://doi.org/10.1016/j.jobe.2020.101481.
[78] N. Kim, J. Gero, Neurophysiological responses to biophilic design: a pilot experiment using VR and EEG biomimetic inspired architectural design view project design neurocognition view project. https://www.researchgate.net/publication/359892380, 2022.
[79] A. Mahrous, K. Dewidar, M. Refaat, A. Nessim, The impact of biophilic attributes on university students level of Satisfaction: using virtual reality simulation, Ain Shams Eng. J. 15 (2024) 102304, https://doi.org/10.1016/J.ASEJ.2023.102304.
[80] A. Latini, S. Torresin, T. Oberman, E. Di Giuseppe, F. Aletta, J. Kang, M. D'Orazio, Effects of biophilic design interventions on university students' cognitive performance: an audio-visual experimental study in an immersive virtual office environment, Build. Environ. 250 (2024) 111196, https://doi.org/10.2139/ssrn.4585084.
[81] X. Zeng, P. Luo, T. Wang, H. Wang, X. Shen, Screening visual environment impact factors and the restorative effect of four visual environment components in large-space alternative care facilities, Build. Environ. 235 (2023), https://doi.org/10.1016/j.buildenv.2023.110221.
[82] T. Schubert, H. Regenbrecht, F. Friedmann, The experience of presence: factor analytic insights, Presence: Teleoperators and Virtual Environments, Presence: Teleoperators and Virtual Environments 10 (2001) 266–281. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.69.3630.
[83] B.G. Witmer, M.J. Singer, Measuring presence in virtual environments: a presence questionnaire, Presence Teleoperators Virtual Environ. 7 (1998) 225–240, https://doi.org/10.1162/105474698565686.
[84] S. Nishiike, S. Okazaki, H. Watanabe, H. Akizuki, T. Imai, A. Uno, T. Kitahara, A. Horii, N. Takeda, H. Inohara, The effect of visual-vestibulosomatosensory conflict induced by virtual reality on postural stability in humans, J. Med. Invest. 60 (2013).
[85] R.S. Kennedy, N.E. Lane, K.S. Berbaum, M.G. Lilienthal, Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness, Int. J. Aviat. Psychol. 3 (1993) 203–220, https://doi.org/10.1207/s15327108ijap0303_3.
[86] A. Latini, S. Torresin, T. Oberman, E. Di Giuseppe, F. Aletta, J. Kang, M. D'Orazio, Effects of Biophilic Design interventions on university students' cognitive performance: an audio-visual experimental study in an immersive Virtual office Environment, Build. Environ. (2024) 111196, https://doi.org/10.1016/J.BUILDENV.2024.111196.
[87] M. Pasini, R. Berto, M. Brondino, R. Hall, C. Ortner, How to measure the restorative quality of environments: the PRS-11, Procedia Soc. Behav. Sci. 159 (2014) 293–297, https://doi.org/10.1016/j.sbspro.2014.12.375.
[88] J.P. Guilford, Creativity: yesterday, today, and tomorrow, J. Creativ. Behav. 1 (1967) 3–14, https://doi.org/10.1002/j.2162-6057.1967.tb00002.x.
[89] J. Yin, S. Zhu, P. MacNaughton, J.G. Allen, J.D. Spengler, Physiological and cognitive performance of exposure to biophilic indoor environment, Build. Environ. 132 (2018) 255–262, https://doi.org/10.1016/j.buildenv.2018.01.006.

[90] J. Yin, N. Arfaei, P. MacNaughton, P.J. Catalano, J.G. Allen, J.D. Spengler, Effects of biophilic interventions in office on stress reaction and cognitive function: a randomized crossover study in virtual reality, Indoor Air 29 (2019) 1028–1039, https://doi.org/10.1111/ina.12593.
[91] F. Erich, The Heart of Man: its Genius for Good and Evil, Harper & Row Publishers, New York, 1964.
[92] D.L. Woods, M.M. Kishiyama, E.W. Yund, T.J. Herron, B. Edwards, O. Poliva, R.F. Hink, B. Reed, Improving digit span assessment of short-term verbal memory, J. Clin. Exp. Neuropsychol. 33 (2011) 101–111, https://doi.org/10.1080/13803395.2010.493149.
[93] S. Putze, D. Alexandrovsky, F. Putze, S. Höffner, J.D. Smeddinck, R. Malaka, Breaking the experience: effects of questionnaires in VR user studies, in: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, ACM, New York, NY, USA, 2020, pp. 1–15, https://doi.org/10.1145/3313831.3376144.
[94] E. Largo-Wight, W. William Chen, V. Dodd, R. Weiler, Healthy workplaces: the effects of nature contact at work on employee stress and health, Publ. Health Rep. 126 (2011) 124–126, https://doi.org/10.1177/00333549111260s116.
[95] S. Aristizabal, K. Byun, P. Porter, N. Clements, C. Campanella, L. Li, A. Mullan, S. Ly, A. Senerat, I.Z. Nenadic, W.D. Browning, V. Loftness, B. Bauer, Biophilic office design: exploring the impact of a multisensory approach on human well-being, J. Environ. Psychol. 77 (2021) 101682, https://doi.org/10.1016/j.jenvp.2021.101682.
[96] A. Latini, L. Marcelli, E. Di Giuseppe, M.D. Orazio, Investigating the impact of greenery elements in office environments on cognitive performance , visual attention and distraction : an eye-tracking pilot-study in virtual reality, Appl. Ergon. 118 (2024) 104286, https://doi.org/10.1016/j.apergo.2024.104286.