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Review

Application of Virtual Environments for Biophilic Design: A Critical Review

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Abstract: Biophilic design as a new design approach promotes the integration of natural elements into the built environment, leading to a significant impact on human health, well-being, and productivity. On the other hand, scholars have explored Virtual Environment (VE) to create virtual nature and provide a complex experience of exposure to natural elements virtually. However, there is a lack of understanding about such studies in general, which use VE as a reliable tool to support biophilic design. Thus, the authors conducted a literature review on the applications, capabilities, and limitations of VE for biophilic design. The literature review shows that VE is capable of supporting critical features of biophilic design studies such as representing combinations of biophilic patterns, providing multimodal sensory inputs, simulating stress induction tasks, supporting required exposure time to observe biophilic patterns, and measuring human's biological responses to natural environment. However, factors affecting user's experience of a virtual biophilic environment exist, such as VE experience dimensions, user-related factors, cybersickness, navigational issues, and possible limitations of VE sensory input. Overall, biophilic design studies in VEs are still limited. Nevertheless, there are many opportunities for further research in this field.

Keywords: biophilic design; virtual environments; virtual natural environment; restorative environments; experience design; health and well-being

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1. Introduction

Throughout the past 100 years, the global urban population has increased dramatically [1]. The rapid growth of urbanization has affected human lives in many ways and significantly influences human health [2]. Urban environments are more crowded and often more stressful than rural environments [3]. Studies show that, on average, Americans spend 90 percent of their time indoors [4,5]. Modern lifestyles often lead to the exclusion of the natural environment [6], which is likely to be a contributing factor to various health and well-being issues.

Biophilic design attempts to reconnect people with nature by integrating and applying natural features into the built environment [7]. Biophilic design application ranging in scale from interior design, building design to parks, streetscapes, and urban design. Existing literature shows that biophilic design and exposing individuals to nature and natural environments can improve their overall health and well-being. For example, many studies explored and reported various psychological and cognitive benefits of natural and biophilic environments, such as improved cognitive performance [8], positive affective reactions [9] and affective functions, including problem-solving and creativity [10], improved productivity [11,12], stress reduction [11,13], the potential for restoration and fatigue reduction [14], psychological effects, e.g., positive emotions [15], positive mood and feelings of vitality [10], positive association with physical activity [16], increased feeling of safety in urban scale [17], and negative association with mortality [18].

Besides actual natural elements, scholars studied the benefits of mediated nature and natural elements (e.g., [19–21]). Most recently, researchers took advantage of virtual reality (VR) technology to provide more immersive experiences for individuals and expose them to natural elements virtually (e.g., [22,23]). In fact, VR technology has been applied in Architecture, Engineering, and Construction (AEC) to facilitate visualization, design review, and decision making (e.g., [24–26]), AEC education (e.g., [27,28]), and construction safety and training (e.g., [29,30]).

In the literature, very few studies reported investigating the application of virtual natural environments for biophilic design [31–34]. Therefore, there is a gap in the literature with respect to the effectiveness of VE for better understanding biophilic elements and patterns. Moreover, the effectiveness of VE on restorative environments design and human biological responses to them is still a hot research topic. In this work, the authors review several works that demonstrate the effectiveness of VE for virtual natural environments and biophilic design.

Although the deficiencies of studies using VE for biophilic design are occasionally mentioned in the literature, a comprehensive study reviewing the limitations of existing works is absent. In this work, the authors explored limitations of VE for biophilic design and potentials for future studies.

The paper is organized as follows: in Section 2, the objective and methodology of the paper are defined. The definition, critical features, classification, and related theories of biophilic design as well as VEs are explained in Sections 3 and 4, respectively. In Section 5, a review of virtual natural environment studies is discussed. Studies in virtual natural environments are classified to highlight the parameters for biophilic design studies in VE. In Section 6, applications, capabilities, and limitations of VE for designing biophilic environment experience and related key factors, as well as possible future research directions, are presented. Section 7 includes conclusions based on the findings.

2. Objective and Methodology

The objective of this study is to understand the state of knowledge regarding applications, capabilities, and limitations of VE for biophilic design, and then identify potential gaps for future research. To this end, the study, first, focuses on features, theories, and applications of biophilic design and VE, and then reviews the application of VE for biophilic design. The authors took four major steps:

- First, a literature review is performed to understand biophilia, biophilic design, related health theories, categories, and the patterns of biophilic design.
- Next, VEs, their features, classification, experiential design in VE, and their applications are studied.
- Then, a review of studies investigating the applications of virtual natural environment, including mediated and simulated environments, are presented. In this step, applied methods and key factors of existing research are highlighted and major parameters for natural environment and biophilic design studies in VE are identified.
- Finally, based on above reviews, contributing factors to design biophilic environment experience are identified, and the status, applications, capabilities, and limitations of VEs for biophilic design, as well as the future research directions are presented.

In this research, published peer-reviewed journals, conference proceedings, books, and theses have been reviewed. The main search engine of the study is Google Scholar, which is a database frequently employed by scholars across different domains. Additionally, it has a high source coverage and citation tracking capability across all disciplines and also non-journal sources [35,36]. To achieve the research objective, aforementioned major steps are conducted as follow:

For the first step, to find the research keywords and relevant literature, "biophilic design" is searched in Google Scholar. The authors limit the search to articles include "biophilic design" in their title. A total of 403 articles are found. After initial screening of titles, top ten major and highly cited references are manually reviewed. Keywords, such as "biophilic design", "biophilia", "exposure to nature", and "natural elements" are extracted from the references' list of keywords or topics, in case they are books, and picked as the primary search keywords. In addition, "restorative environment", "attention restoration", "stress recovery", "health", and "well-being" are added as search keywords. Including these keywords is important sine biophilic design improves human health and well-being in the built environment and most biophilic design references also highlight these aspects.

Next, Google Scholar is searched again with these search rules: (biophilic design) AND (biophilia OR exposure to nature OR natural elements) OR (biophilic design) AND (restorative environment OR attention restoration OR stress recovery OR health OR well-being). After applying the search rule, around 4200 results are found. The titles, abstracts, and keywords of the first 150 articles are screened to find potentially relevant publications. The inclusion criteria for this step are references that (1) focused on AEC and health domains; (2) represented key concepts, theories, and applications of biophonic design; (3) published from 2006 to 2020. To ensure the quality of included references, peer-reviewed journals and books published by well-known publishers are considered. Thirty-two references are selected for more in-depth study of biophilic design (step 1).

For the second step, the literature search is started by using the keywords "virtual environment", "immersive virtual environment", or "virtual reality" in their title. Then, from 2490 search results, fifteen most cited references are selected. After preliminary screening of the references, potential keywords are recoded. Next, from pool of keywords and based on the objective of this step, which is identifying key features and applications of VE, these keywords are refined for a broader search: "virtual environment", "immersive virtual environment", "virtual reality", "presence", "immersion", "sensation", "VE stimuli", and "VE design".

Like step 1, Google Scholar is searched again according to selected keywords and the following search rule: (virtual environment OR immersive virtual environment OR virtual reality) AND presence AND immersion AND sensation AND stimuli AND design. After manually reviewing the first 200 of about 1000 search results, potentially relevant publications are selected for further studies. The inclusion criteria for this step are (1) references representing key concepts, features, and applications of VE (3) references from 1991 to 2020. In this step (step 2), a total of sixty-three publications are chosen for a comprehensive review.

In the next step, to review the virtual natural environment applications for biophilic design, "biophilic design" AND "virtual environment" is searched jointly in Google Scholar. A total of 55 articles are retrieved. Similar to the previous steps, after preliminary screening titles, abstracts, and keywords, "virtual nature", "virtual natural environment", and "virtual biophilic environment", which are the focus of this research, are selected and utilized for broader search.

The search rule for this step is "virtual nature" OR "virtual natural environment" OR "virtual biophilic environment" and about 9100 results are retrieved. A total of 250 first results are selected for initial screening. Finally, the criteria for selecting the reviewed references from the initial search are: (1) recently published peer-reviewed journal papers, conference proceedings, theses, or dissertations; (2) research in the fields of AEC and design, health and therapy, or VE related domains, such as informatics; (3) empirical studies focused on applications rather than definitions and general concepts; (4) studies applying quantitative, qualitative, or mixed research methods. Based on these criteria, thirty-six references are selected (step 3), which includes all the virtual biophilic design studies, to the best authors knowledge, as well as samples of natural environment studies in VE. The focus of study is on research from 2016 to 2020. However, ten notable research studies published before 2016, which are highly cited or utilize different methods, are also included in the review. Then, the selected references are analyzed and classified according to factors extracted from steps 1 and 2. For each study, information on research design and method, data collection method, features of virtual biophilic environment, delivery mode, and VE system are extracted and classified. The classification goal is to identify research methods and key parameters of biophilic design studies in VE.

In the final step (step 4), based on searches results found in previous steps, sixty-six references are comprehensively reviewed to identify the status, applications, capabilities, and limitations of VE for biophilic design. At the end, future research potential of VE for biophilic design studies are proposed.

3. Biophilia and Biophilic Design

The word biophilia was first made well-known by psychoanalyst Erich Fromm in the 1960s [37]. Fromm utilized the term biophilia in the Anatomy of Human Destructiveness and explained it as "the passionate love of life and of all that is alive." [38] Edward O. Wilson, a Harvard biologist, extended the meaning of the word and proposed the biophilia hypothesis in 1984 as a natural inclination to "life and lifelike processes" [39]. The design style that reconnects people with nature and incorporates natural structures into the built environment is called biophilic design [7].

3.1. Biophilic Design for Outdoor/Exterior and Indoor Environments

Biophilic design studies include investigating both outdoor and indoor environments. Exterior biophilic design comprises a wide range from buildings to blocks, streets, neighborhoods, communities, regions, and in general urban design [40,41].

In addition, biophilic design is helpful for the design of indoor built environments. For example, in healthcare and hospital environments, the presence of nature and biophilic elements has been explored in various research. The literature shows that views to the natural environment and implementing biophilic patterns in healthcare and healing environments have positive impacts on individual's well-being, reduce stress and pain, and enhance patients' recovery from illness and surgery (e.g., [42–44]). Therefore, it is recommended as a guideline for the design of hospital and healthcare facilities by the American Institute of Architects [45]. Moreover, since businesses and office environments are stressful and productivity is very important in such environments, biophilic design captures the attention of designers for office and workplace design (e.g., [12,20,33,34]). It is also incorporated in the design of educational [46–48], residential [49,50], and commercial spaces [51].

3.2. Biophilia and Health Theories

There are two prominent and relevant theories in nature and human health research:

- Attention Restoration Theory (ART): a theory refers to a cognitive framework concentrating on the recovery of directed attention fatigue [14,52]. To illustrate, directed attention is very demanding, and attentional fatigue can happen after completing difficult tasks and facing environmental stimulation (e.g., traffic, advertisement, etc.). Directed attention fatigue may result in failure to recognize interpersonal cues and inability to plan. Based on ART, dealing with environments with fascinating triggers (e.g., natural settings) captures involuntary attention and can restore directed attention and cognitive recourses. Fascinating stimuli refer to elements or events that grab an individual's attention effortlessly [53], which may affect a person in positive "soft fascination" or negative way "hard fascination". From this point forward, fascination is used instead of soft fascination, which triggers human attention effortlessly and provides a pleasant experience for humans. ART suggests that natural environments are restorative environments because they capture involuntary attention. As a result, it is expected that individual performs required tasks directed to attention better after exposure to restorative environments. Besides fascination, there are three other key characteristics for a restorative environment, as stated by ART. They include "being away" (psychological or physical escape form routine environment), "coherence" (perceiving elements as a coherent picture), and "compatibility" (compatibility of environment's attributes and person's expectations) [52].
- Stress Recovery Theory (SRT): a psycho-evolutionary theory proposed by Ulrich [13] suggests that non-threatening natural environments are restorative environments

and provide a more positive emotional state and decrease physiological arousal. Based on SRT, humans prefer natural environment evolution. Engaging with pleasant environment results in reducing stress by improving physiological responses and positive emotions as well as controlling negative emotions and thoughts.

Both theories are related to restoration in natural environment; however, ART highlights human cognition while SRT emphasizes psycho-physiological responses to natural settings.

3.3. Biophilic Design Patterns and Categories

For decades, researchers and designers have attempted to define biophilic patterns and aspects of nature that have an impact on humans to improve their satisfaction and well-being in the built environment. There are various attempts in this field to extend the biophilia hypothesis, including a framework for biophilic design that is adaptive and applicable to different built environments and provide the experience of nature in those environments. The most acknowledged biophilic design patterns and categories are proposed by Kellert [54–57] and Browning et al. [7,58]. Biophilic categories, patterns, and elements or features are summarized based on [7,55–58] in Table 1. These categories and patterns are employed to review and analyze virtual natural environments literature in Section 5.

Table 1. Summary of biophilic categories, patterns, and elements or features based on [7,55–58].

Category	Patterns	Description	Elements or Features
Natural Elements	Visual Connection with Nature [7]	View to natural environment and living systems (real or simulated)	Plants Animals Water Fire Habitats and ecosystems Image of nature Views and vistas
	Non-Visual Connection with Nature [7]	Sensory stimuli, except visual, that positively refer to living systems or nature	Smell of Plants Animal sounds Waterfall sound Fireplace sound
	Light	Various intensities of real or simulated light and shadow similar to conditions that occur in nature	Natural light and shadow Filtered light Warm light Reflected light
	Thermal and Airflow Variability [7]	Gentle changes in thermal and airflow variables that mimic nature (real or simulated)	Surface temperature Airflow (e.g., wind, breeze) Humidity
Natural Analogues	Natural material	Materials and elements from nature	Natural materials
	Natural Shapes and Forms [56]	A symbolic reference to forms and shapes that exist in the natural environment	Natural geometries Natural colors Biomimicry Biomorph
	Natural Patterns and Processes [56]	A symbolic reference to patterns and processes that exist in the natural environment	Growth Change and age Patterned wholes Integration of parts to wholes Fractals Central focal point Transitional spaces Bounded spaces

Table 1. *Cont.*

Category	Patterns	Description	Elements or Features
Experience of Place and Space	Evolved Human–Nature Relationship [56]	Spatial configurations in the natural environment. It includes human's desire to feel and experience beyond surroundings	Refuge and prospect Discovery and exploration Mastery Curiosity Protection and security Order and complexity
	Place-based Relationship [56]	Place attachment and individual's natural for familiar places	Historical, cultural, geographic, or ecological connection to place Culture and ecology integration Landscape orientation Landscape features and ecology Indigenous materials Spirit of place

4. Virtual Environments

Virtual Environment (VE) is an environment created through computers and experienced by participants [59]. It is considered as "communications media" [60] that enhances the communication between computers and humans [61]. It transforms the digital representations into a perceptible experience and may represent either a fictional or an existing actual environment. The advanced version of VE is VR, which offers a rich, vivid, and complex experience for users. According to the dictionary, VR is "an artificial environment which is experienced through sensory stimuli provided by a computer and in which one's actions partially determine what happens in the environment" [62]. In this research, both three-dimensional (3D) simulated and mediated (e.g., photo and video) environments are considered as VE and studied.

4.1. Immersion and Presence

Two important characteristics of VEs are "immersion" and "presence". Immersion is described as "the technical capability of the system to deliver a surrounding and convincing environment with which the participant can interact" [63]. The level of immersion depends on the VE systems' properties and not on human experience. There are several factors that influence immersion, such as visual realism, display parameters, virtual body representation, engagement of body, haptics, and sound [63].

On the other hand, presence refers to "the sense of being in an environment" [64,65]. In the context of VE studies, presence is the sense of being in places where VEs suggest, rather than where one is physically situated [66]. VE effectiveness is related to a participant's sense of presence. Besides presence, there are concepts of "social presence" and "co-presence" that are the "sense of being together" with others in VEs [67]. To expand the concept of presence, other causes of presence are summarized as follows [66–73]:

- Technology factors, including sensory and realism factors [66], such as multimodal information consistency [69] and presentation, environmental richness, information consistency with objective world, sense realism [66], meaningfulness of media content [70] and ease of navigation and equipment comfort [71].
- User variables, such as previous experience and familiarity with medium, adaption and learning of system features, mood, and gender, and age [69,72,73].
- Social factors, which is the interaction between users and technology [67].

There are also different physiological and psychological effects associate with presence: arousal, mood (e.g., enjoyment and delight), memory and persuasiveness of media content, task performance, psychological side effects (e.g., motion sickness, simulation sickness), and psychological desensitization to exposed trigger (especially for long-term use) [68].

4.2. Presence and Experiential Design in VE

Chertoff proposed a novel perspective to presence in 2008 [74]. He believes traditional approaches to presence are information-centric, while effective VEs should be knowledge-centric. So, it is required to improve experience design in VE [74]. He believes presence is a multidimensional exploratory experience. To create a compelling experience, the product or environment needs to engage physical, cognitive, affective, active, and relational dimensions [75].

Therefore, to have more realistic results and improve participants' presence in VEs, researchers need to design virtual experience. VE experience includes creating the VE as well as designing a scenario and participant related factors. Virtual Experience Test (VET), a questionnaire proposed by Chertoff et al. [76], measures holistic experience based on five dimensions of experiential design. It analyzes the experiential design through storytelling (communication and interaction with elements of VE), haptic (application of haptic sensory), sensory content (utilization of non-haptic sensory input), task completion, and active factor (user's self-feeling as a character in VE).

Dimensions of experiential design applied toward VEs are [74]:

- Sensory dimension: all sensory inputs generated through hardware and software.
- Cognitive dimension: different types of task engagement or mental engagement related to participant's motivation, task meaningfulness, and continuity.
- Affective dimension: an effective mimic of user's emotional state in the VEs, same as the real-world environment.
- Active dimension: the degree of personal relation and connection to VE, scenario, and other avatars
- Relational dimension: experience related to co-presence and social presence.

4.3. Classification of VR Systems

VE can be perceived and experienced through various representations and forms. Muhanna [77] proposed a taxonomy that classifies VR systems into non-immersive, partially immersive, and fully immersive.

- Non-immersive systems: this category is the basic type of VR systems and can be employed without any special input or output devices. Non-immersive systems provide the least immersion presented by 3D graphics and are screen-based and pointer- driven [77]. With non-immersive systems, users are able to interact with VE through computer screens, but not immersed in it [78].
- Partially immersive systems: this group includes enhanced systems that improve user's immersion. They display VE on a large screen via a single projector [77]. They support partial body tracking or 3D experience of scenes through special gloves or special goggles, respectively.
- Fully immersive systems: the ultimate version of VR systems supports stereoscopic views of a scene [77]. Binocular head-based, such as Head Mounted Displays (HMDs), and room-based VR technology, such as Cave Automatic Virtual Environments (CAVEs), are subcategories of fully immersive systems.

In the present study, VEs include all the environments that present via VR systems, such as non-immersive screens, partially immersive systems, including projector-based VR systems, and fully immersive HMDs or CAVEs.

4.4. Sensation and VE Sensory Input

Among all human senses, vision has the highest information gathering function and capture a large set of information at the moment [79]. Similarly, in VE, visual stimuli provide the most information and are considered as the core sensory cues that VE developers mainly focus on [80]. Besides visual cues, auditory sensory stimuli, such as audio recordings, may provide high fidelity audio experience in VE. Wearing headphones and providing surround sound in CAVE-like environments are examples of auditory systems for VEs [80]. Other VE sensory equipment includes haptic feedback devices, which is used less than auditory sensory cues [81]. Comparing to other sensory stimuli, olfactory [82] and thermal stimuli [83–86] are also effective in perception, cognition, and memory. They are not as frequent but emerging in VE studies. The combination of consistent sensory inputs can increase the level of immersion and influence participant's sense of presence in VE [78].

4.5. Applications of VE in AEC

During the past decades, VE has become popular in different fields. Psychology and therapeutic applications [63], military training [87], education [88,89], and entertainment [90,91] are some examples that widely take advantage of VE, specifically VR, in their fields. In addition, in recent years, VR has had significant growth in AEC industry. VR is potentially a useful tool for behavioral and human-environmental research [92]. It can simulate scenarios that are risky (e.g., emergency situations), costly (e.g., design review), or impossible to be built [77,93]. Some major applications of VR technology for AEC include:

- Visualization, design review, and decision making [24,25,82,94–103].
- Design review for energy and user's behavior [24,104,105].
- AEC education [27,28,106].
- Construction safety and training [29,30,107–109].
- Structural analysis training [110–112].

Regarding visualization, design review, and decision making, VE enables architects and designers to test hypothetical designs and study 1:1 scale design options [100]. Reviewing and manipulating VE during the design process facilitate visualization, perception of spaces, and pre-occupancy spatial evaluation of the design [103].

5. A Review of Virtual Natural Environment Studies

As explained in the previous section, VE facilitates visualization and design review. Therefore, it would be a valuable tool to study natural environment and biophilic design as well. According to the literature, there are two different perspectives on application of VE to study natural environments. From one point of view, scholars study the application of VEs for humans to access nature. They believe that in some circumstances, real nature is not available, or accessing it might be difficult (e.g., mobility constraints) or time-consuming. Therefore, when real nature is not available, exposure to simulated or mediated nature can be an alternative to replace the actual nature and result in similar restorative effects of experiencing the actual natural environment [113–115]. This can be considered as an example of the first biophilic pattern, visual connection with nature.

From another perspective, the applications of VE to study biophilic environment as a research tool has been investigated. VE is capable of supporting natural and biophilic environment research by providing different types of stimuli, enabling participants to have an interactive experience and actively explore VEs, and allowing scholars to systematically manipulate research stimuli, have full control over them, and maintain experimental control [92,116]. VE also provides other benefits for lab-based experiments, such as randomization as well as control and change of experimental conditions and context variables, collecting perception data, and providing immediate feedback. It should be considered that VE studies need to be tested on internal, external, construct, criterion, and ecological validity. Among these, ecological validity (realistic representation of the environment as well as the realistic behavioral response of participants) is important, especially for studies that using VE as a predictive tool [117,118].

This study considers both aforementioned applications of VE in regards to natural environments, but the focus is on the latter.

5.1. Review and Classification of Studies in Virtual Natural Environment

In this section, a literature review of studies using VE to evaluate the effectiveness of virtual natural environments is presented. Unfortunately, only a limited number of studies on biophilic design using VE has been reported so far. However, besides the design domain, human interaction with nature is also explored using VE in psychology and human health and therapy domains. Therefore, in this study, the authors also included research that utilize virtual natural settings in various domains, and based on that, proposed research methods and essential parameters for future studies on biophilic design in VE.

In the following, 36 studies from 2006 to 2020 are studied ([19–23,31–34,51,113,119–143]). The studies are categorized based on 16 factors and their subfactors explained in the following:

1. Biophilic categories: this includes three major categories; natural elements, natural analogues, and experience of place and space.
2. Biophilic patterns: patterns are summarized in Table 1 based on Kellert and Browning's studies [7,55–58], which includes: "visual and non-visual connection with nature" [7], light, thermal and airflow variability [7], natural material, "natural shapes and forms, natural patterns and processes, as well as evolved human–nature and place-based relationship" [56].
3. Biological responses: biological responses related to natural environment are "stress reduction", "cognitive performance", and "emotion, mood, and preference" [7].
4. Collected data and measurements: physiological data, psychological data, cognitive data, and VE validation data. Types of tests and tasks that are carried out in the studies for data collection are provided in Table A2.
5. Subjects: based on nature-health relations, subjects in the studies may be healthy or patient.
6. Stress or mental fatigue induction: stress-inducing tasks may deploy as stressor before, during, or after exposure to natural environment. However, in some studies, mental fatigue induction tasks are considered according to research interest. Stress induction or mental fatigue tasks can be part of the design to assess biological responses in relation to potential stress recovery or restoration effects of virtual natural settings. Therefore, the Subfactors include pre-exposure, peri-exposure, post exposure, and none.
7. Natural environment settings: based on reviewed studies, the subfactors are biophilic indoor environment, biophilic outdoor environment, urban green space or streetscape, and wild natural environments (such as a forest).
8. Delivery mode of virtual nature: this can be either simulated or mediated environment [113]. Therefore, the delivery mode is classified to virtual 3D model, 360° video, 2D video, 360° photo, and static image.
9. VE systems: VE systems are categorized into fully immersive (HMDs or CAVEs), partially immersive (projectors), non-immersive (screens), and none.
10. VE presence: the studies are either single-user or multi-user system.
11. Sensory inputs: sensory inputs include visual, auditory, olfactory, tactile, and thermal stimuli and wind.
12. Research design: the design of research includes total settings/contexts and total conditions.
13. Natural environment presentation: the subcategories are reality vs. virtual environment and virtual vs. virtual environment.
14. Sample size: sample size of studies is categorized to less than 20, 20–50, 51–100, and over 100.
15. Duration of exposure to each condition: the subcategories are less than 10 min, 10–20 min, 21–60 min, more than one hour, and more than to one day.
16. Total duration of each session: total duration of each session is less than two hours, more than two hours, or more than one day.

The reviewed studies in the literature are listed and compared based on aforementioned factors in the Appendix A, Table A1 (factors 1–4), Table A2 (factor 4), Table A3 (factors 5–7), Table A4 (factors 8–11), and Table A5 (factors 12–16). In the following sections, the reviewed studies are analyzed and discussed to point out the research method, design process, virtual natural environment's features, and parameters of virtual biophilic environment studies.

5.2. Analysis and Discussion of Reviewed Literature

The literature review shows consistency in applications of and virtual natural environments for biophilic design and restoration.

- Biophilic categories and patterns: among three major categories of biophilic design, natural elements are utilized the most (100%). Natural elements followed by natural analogues are easier to understand and implement compared to the experience of place and space. Thus, it might be the reason for such a pattern. For biophilic indoor environments, natural elements and natural analogues are common categories. Natural analogous has been explored, especially in most recent studies (2019 and 2020). Regarding biophilic patterns, the three most reported patterns are visual connection with nature (100%), light (84%), and followed by non-visual connection with nature (53.6%). In some studies, the authors consider wild natural environments, such as forest or coast, as their natural setting. In these studies, visual connection with nature and light are common biophilic patterns. Depending on research interests, there might be some non-visual connection with nature, including nature sounds (e.g., birds tweeting sound, breeze, etc.) or natural odors (e.g., forest, flowers, etc.). In addition, some studies consider evolved human–nature relationship pattern (13%), specifically prospect, and refuge features [23,119,124,126,135]. Figure 1 shows the distribution of reviewed studies based on biophilic patterns.

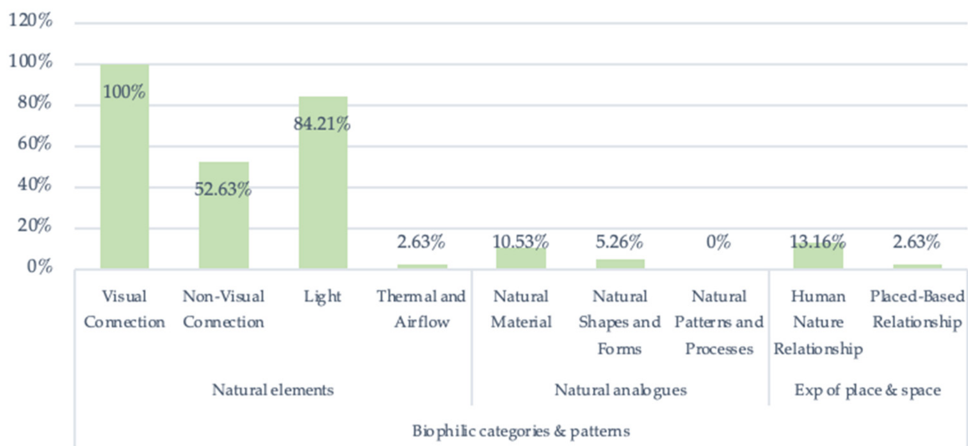

Figure 1. Distribution of the reviewed studies employing virtual natural environment based on biophilic patterns.

- Biological responses: all three responses, "stress reduction", "cognitive performance", as well as "emotion, mood, and performance," have been studies based on research domain and interest. Attention restoration and/or stress recovery theories are studied in most of the reviewed literature. According to health-related theories discussed in Section 3.2, psychophysiological responses to natural settings are emphasized by SRT, while cognitive responses are highlighted by ART. Based on the literature, emotion, mood, and performance (73.6%) as well as stress reduction (71%) are the most reported biological responses and there is less research on cognitive performance (34.2%).
- Collected data: psychological data is the most reported collected data (86.8%) among the reviewed literature. Some researchers also collect physiological data (60.5%) to validate responses and results. Cognitive data is the least reported collected data (34.2%). The distribution of reviewed literature based on biological responses and collected data is illustrated in Figure 2.

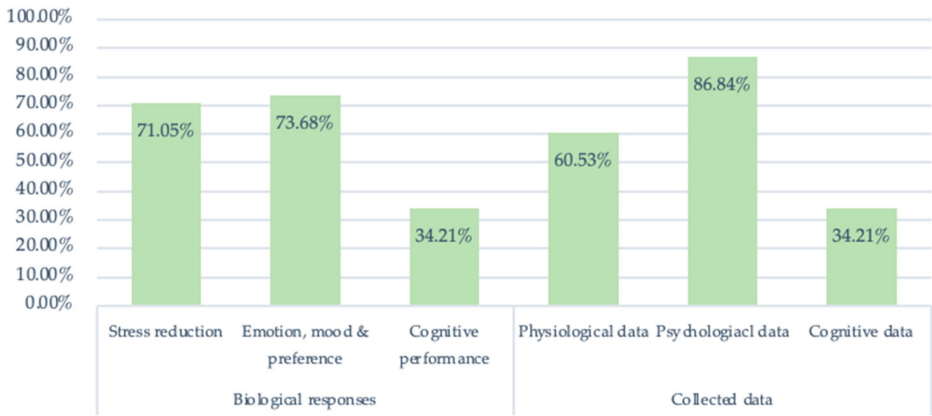

Figure 2. Distribution of the reviewed studies employing virtual natural environment based on biological responses and collected data.

- Measurements: there is a wide range of methods, tests, and tasks for data collection. Recording heart rate (HR) is the most reported measurement method for physiological data. Moreover, heart rate variability (HRV), skin conductance level (SCL), and/or blood pressure (BP) have been utilized in many studies. For psychological data related to emotion, mood, and performance, several types of self-rated questionnaires are used. The Positive and Negative Affect Schedule (PANAS) and Perceived Restorativeness Scale (PRS) are the most reported standard psychological measurements. PANAS assesses participant's mood [142,144] and the PRS is a four-factor model that evaluates the restorative quality of environment through four elements of ART [145,146]. Regarding cognitive data, several quizzes and tests are reported. One of the cognitive tests is the Attention Network Test (ANT), which measures attentional performance of individuals in a single integrated task through alerting, orienting, and executive control [147,148]. In addition to ANT, reaction time tests, working memory tests, Stroop task, Droodle task, and Compatibility task are some examples of cognitive tests and tasks that have been employed in the reviewed literature. In some VE research, there are also VE-related measurements, including the Igroup Presence Questionnaire (IPQ), VE system ease of usability and navigation [137], and the Simulator Sickness Questionnaire (SSQ) [140].
- Subjects: although there are many studies on patients with mental disease in the psychology and therapy domain, this reviewed literature is focused on healthy subjects. Except in [121] (patients with substance use disorder), [122] (patients with cognitive or physical impairments), and [143] (patients with stress and/or burnout syndrome), other studies involved healthy users (92%). It is noteworthy that although Gerber et al. [134] studied healthy patients in an intensive care unit (ICU), he proposed that VR stimulation in ICU can also be possible and beneficial for critically ill patients.
- Stress or mental fatigue induction: since many studies worked on natural environments as restorative environments, different types of stress or mental fatigue inducting tasks are utilized pre- (44.7%), peri- (21%), or post (26.3%) exposure to the natural environment. The Trier Social Stress Test (TSST) [124,130,136], Paced Auditory Serial Addition Test (PASAT) [129], and various arithmetic tests [34,113,133,140] are examples of stress inducing tasks to stimulate user's stress level. TSST is a widely used protocol that triggers participant's social stress in laboratory settings [149], and PASAT consists of a couple of questions pertaining to mental mathematic calculation skills [150]. In addition, some physical stress inducting tasks, including cold pressor task and undergoing dental treatment as a stressor [131], are reported in the literature. Besides research that studied cognitive performance, some studies used cognitive tests only as a stressor to create mental fatigue in subjects in the pre-restoration part (e.g., [34,123,133]).

- Natural environment setting/context: wild natural scenes, such as forest environment, which may include diverse foliage, birds singing, and various smells, are considered as natural environment settings in many of the reviewed literature (68.4%). Urban green spaces, e.g., public parks in urban context, is also considered in some studies (l8.4%, e.g., [21,23,123,125]). In the design domain, natural environment settings are mostly biophilic indoor environments (18.4%, e.g., [31–34]) or biophilic outdoor environments (less than 5%, e.g., [51])
- Delivery mode: various delivery modes have been employed, including virtual 3D model (34.2%), 2D videos (28.9%), 360° video (23.7%), static image (10.5%), and 360° photo (7.9%). The 2D and 360° videos are the most reported delivery modes because they are not only realistic but also are easier to get prepared for test compared to virtual 3D models. However, since 2010, simulated restorative environments also has attracted special attentions. Figure 3 illustrates the distribution of reviewed literature based on their delivery mode.

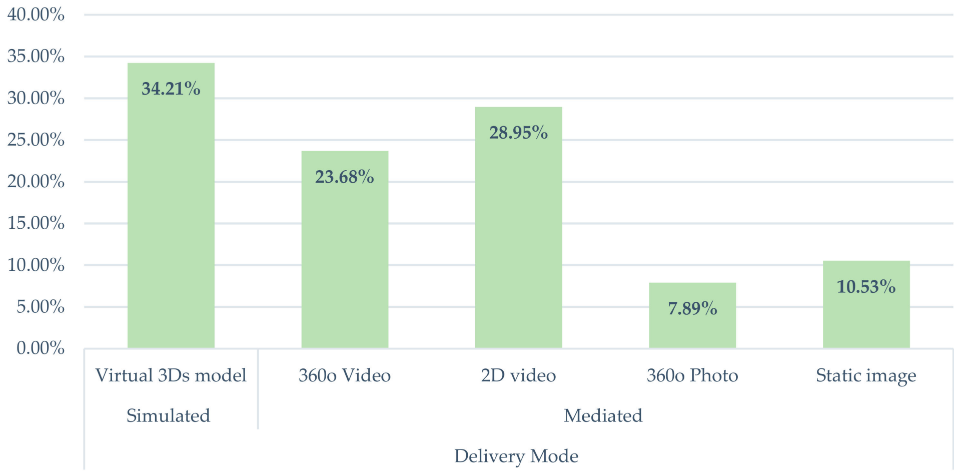

Figure 3. Distribution of the reviewed studies employing virtual natural environment based on delivery mode.

- VE system: depending on delivery mode, utilized VE systems are different. For virtual 3D models, 360° videos, and 360° photos, scholars mostly used fully immersive VE (58%) that provides the most immersive experience for participants. However, few studies employ non-immersive VE (8%) for 3D models, 360° videos, or 360° photos, which requires the least equipment, and can be presented through normal screens. In addition, many studies use 2D video (fixed-angle from one point of view) or static image delivery mode. Since these delivery modes do not provide an immersive experience for users, normal plasma screens are sufficient as a VE system. This VE system is classified as the "none" category, which is employed considerably (39.5%) due to the accessibility of this group.
- VE presence: VE studies are classified into single-user and multi-user based on the number of VE participants that share the same experience [81]. Reviewed literature shows that the single-user system is much more common (100%) in this domain. No research study with a multi-user system for biophilic design in VEs has been found.
- Sensory inputs: as expected, visual stimuli are the major sensory inputs in reviewed studies. In addition, auditory stimuli (55.2%), followed by olfactory cues (10.5%, e.g., [123,125,137,139]), tactile (less than 3%, [139]), thermal, and wind (less than 3%, [133]), are considered in researches. Generally, study on various sensory inputs especially draw attention in the psychology and informatics domain.
- Research design: based on research interest, scholars design different settings and conditions for their study. Most studies (about 79%) consider one or two major settings and design various conditions based on that. For example, Tabrizian et al. [23]

study 18 different conditions to evaluate design elements. On the other hand, some researchers focus on only one setting and study factors, such as natural elements of the environment [51], immersion [113], VE interaction [135], sensory inputs [137].

- Natural elements presentations: since the literature review focuses on virtual natural environments, different research conditions and natural elements are presented and studied in virtual format (3D model, video, or photograph, 76.3%). There are also some research studies that explore natural elements presentation in virtual environment vs. actual natural environment (reality) (21%, e.g., [22,31,33]).
- Sample size: most research considers a small size sample (20–100) (71%). Few studies design the research for less than 20 (15.8%) or over 100 (13%) samples.
- Duration of exposure to each condition: although exposures of longer than 10 min are recommended for change in restorativeness [137], there are many studies with an exposure of fewer than 10 min (52.6%) to the natural environment. Overall, the literature shows that a 20-min exposure to natural elements is effective for restoration and human biological reactions. Therefore, most of the reviewed studies consider an exposure of up to 20 min (92.1%) to each condition for biophilic studies. However, based on a recent study [34], the impact of exposure to the biophilic environment on physiological responses is immediate, especially in the first four minutes of exposure. Figure 4 highlights the distribution of reviewed literature based on duration of exposure to each condition as well as employed sensory inputs and sample size.

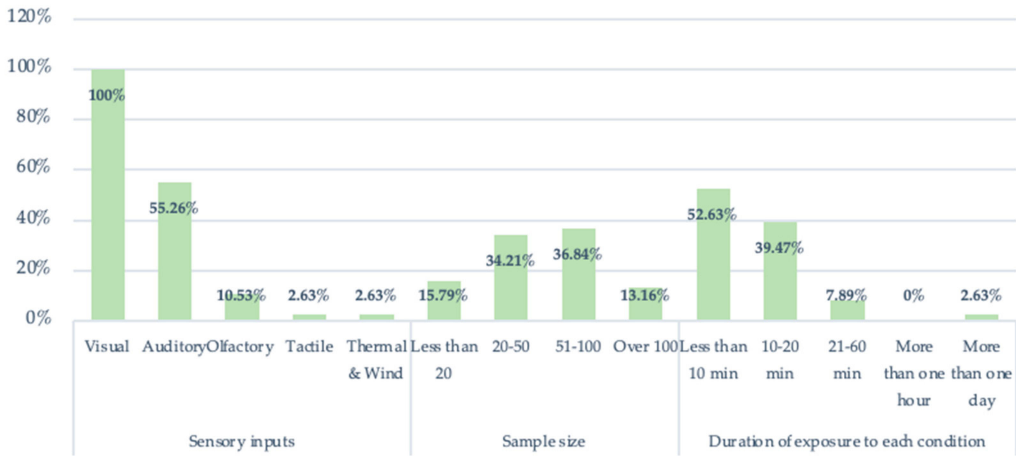

Figure 4. Distribution of the reviewed studies employing virtual natural environment based on sensory inputs, sample size, and duration of exposure to each condition.

- The total duration of each session: the total duration of each session is mostly less than two hours (94.7%). However, there are some studies (e.g., [20]), especially in the psychology domain, which investigate the individual's performance and biological responses under real circumstance over several weeks or months.

6. Design Biophilic Environment Experience in VE: Applications, Capabilities, and Limitations

In order to study biophilic design in VE, scholars need to design virtual experience highlighting biophilic elements in VE. An important opportunity of VE experience is spatial experience, which currently receives less attention [151]. In general, the architectural spatial experience is related to the concept of human-centered design and egocentric perception of humans. Consequently, an individual's interpretation of the characteristics of an environment [152] and his or her responses to designed biophilic stimuli significantly impact his or her overall spatial experience of the environment. The simulation of temporal and spatial dimensions and free navigation are important design considerations for creating virtual spatial experiences [153,154].

There is an inclination toward VE experiences that employ spatiality to closely reproduce the physical world. This occurs owning to architects who consider VE primarily as a tool to visualize and design spaces planned for the physical world. However, Brett argues that architects should consider VR as a tool to visualize and design physical space, as well as a tool to design in and of itself [151]. Therefore, they should not design for the virtual world just as they would do for the physical world. In fact, VE spaces have different limitations and opportunities compared to physical spaces. In the virtual world, although physics, material, construction, navigation, and environmental issues are different and there exist different solutions to these issues, recognizability is valuable [151]. Skeuomorphic design leverages archetypal physical forms to offer something tangible to individuals. It is not necessary that the design of the virtual space reproduce the whole features of the physical world. However, virtual space designers can use familiar structures and forms that will assist individuals in perceiving and navigating virtual world.

Besides the aforementioned opportunities, there are some general limitations and challenges associated with the application of VEs for biophilic design. The first limitation is that creating a convincing virtual environment can take a considerable amount of time and requires designers that are familiar with modeling and programming. In addition, an important challenge is the technical limitations of VE systems. Currently, there are a few companies that work on the technical aspects of VR systems to develop well-designed hardware, better tracking systems, and allow users to interact more naturally [78]. The most mentioned challenge associated with using VE systems, especially HMD, is cybersickness. Cybersickness is human's discomfort symptoms or unintended psychophysiological responses experienced in VEs [68,155]. The high immersion of VE and possible mismatched sensory information between visual and vestibular systems may cause cybersickness, which limits certain types of navigations in VE. Many studies support the idea that cybersickness and user's task performance in VE have an inverse correlation [156,157]. Therefore, an additional challenge that may arise is that cybersickness may negatively affect task performance.

In spite of mentioned limitations, by designing virtual biophilic environments, researchers and designers expect the same physiological, psychological, and cognitive responses in regards to virtual biophilic elements and patterns similar to actual natural elements. Therefore, they seek ecological validity for biophilic design in VE that directly associates with to concept of presence. Based on Chertoff [74], presence in VE is a multidimensional exploratory experience. Consequently, to create a compelling experience, designers require to consider dimensions of experience design, including:

- Sensory dimension: although most of the biophilic studies in VE focus on visual stimuli as single sensory input (see Table A4), adding other sensory modalities (e.g., auditory, haptic, olfactory, thermal) improves the user's VE experience [74] and affect biological responses to natural settings [123,139].
- Cognitive dimension: it comprises different types of task engagement or mental engagement in the VE experiment [74], which provides an opportunity to apply the ART theory. This dimension allows studying individual's cognitive framework and task performance after exposure to biophilic environment. Participant's cognitive performance can be measured by validated cognitive tests (e.g., PRS, ANT).
- Affective dimension: it supports the simulation of the user's emotional state in virtual biophilic environments similar to real-world situations [74]. For example, based on the ART theory, elements of "soft fascination" such as wind breezes can create an affectively positive experience [53], which may be replicated in VE. The affective dimension in VE can be assessed by different physiological (e.g., HR, SCL, BP) and psychological (e.g., PANAS) measurements.
- Active dimension: it refers to personal connections with the surroundings (biophilic elements and patterns). An individual's background and past experience, such as childhood experience of nature, can also have an impact on personal connection to biophilic elements and nature [9].

In addition, causes and effects of presence are important and should be considered in VE studies, including:

- Technical factors: immersion and realism.
- User factors: they include mood, age, and familiarity with technology. For example, Weech et al. [158] discussed that people with more gaming experience indicated partially a higher level of presence in VE. Other studies showed that older participants experienced greater difficulties when mismatch or incorrect visual sensory stimuli existed [159], which also had an impact on participants' mobility and balance [160]. Moreover, there are some additional factors related to users that impact biophilia studies in VEs:
  - Gender: this factor has not been studied in-details in literature. However, some studies demonstrated that participants had different responses to biophilic elements based on their gender. For example, Yin et al. [32] showed that during their experiment, female participants spent more time on biophilic elements in VE.
  - Childhood experience of nature: the literature suggests that childhood experience of nature is related to an individual's meaningful relationship with nature and natural environments [161]. This also may affect the perception of the restorative effect of the natural environment [23]. Therefore, it can result in the increase of calming effects of nature for those persons and more motivation to engage with natural elements [9]. In virtual biophilic environment exposure, Yin et al. [32] also found that individuals growing up in rural or suburban areas spent more time engaging with natural and biophilic elements.
  - Individual preferences, as well as differences in perception and cognition: based on information processing theory [162], a perception system creates meaningful representations of numerous sensory stimuli in the external environment and organizes psychological apprehension. On the other hand, the ART theory suggests that the cognitive resources of people can be restored by interacting with attractive stimuli of natural settings [52]. However, individual differences may impact his or her perception and cognition processes, i.e., the way individuals perceive an environment and biophilic stimuli; and, consequently, the potential of the VE's restorativeness [135].

The aforementioned factors should be considered for biophilic design experience in VE. Besides, there are some general parameters for biophilic design studies. Table 2 presents those parameters and general capabilities and limitations of VE as well as VE application for biophilic design and possible future opportunities for further research.

Table 2. Virtual Environment (VE) applications for biophilic design studies and future works.

Parameters of Biophilic Design Studies	General VE Capabilities and Limitations	VE Application for Biophilic Design Studies
Biophilic design categories (Natural elements Natural analogues Experience of space and place)	VE has wide applications in Architecture, Engineering, and Construction (AEC) research for visualization, design review, pre-occupancy evaluation, and decision making (e.g., [25,98,100,102])	Implementing all three categories are reported in the literature (e.g., [32,34,119,124]). Natural analogues and experience of space and place are less reported in the literature, but it is technically feasible to implement.

Table 2. *Cont.*

Parameters of Biophilic Design Studies	General VE Capabilities and Limitations	VE Application for Biophilic Design Studies
Biophilic design patterns	VE has wide application for visualization and design review in AEC. Simulating and representing various design elements, forms, and patterns are possible through features of game engines and VE input devices (e.g., [25,82,99,163]).	Generally, some biophilic patterns are less familiar to participants and less explicit to understand and implement compared to others. For example, participants felt more connected with nature in VE setting with natural light, indoor plants, or a view to nature compared to natural material and forms [32]. "Natural patterns and processes" is more psychological, required precise design, and less clear to participants than green natural elements or material. Therefore, this biophilic pattern is not reported in the literature; however, technically, there is no challenge for simulating this pattern in VE. Regarding thermal and airflow patterns, simulation in VE is also possible through thermal panels and climate chambers. Such simulations are reported in energy and occupant behavior studies [164]. However, comprehensive studies regarding thermal and airflow simulation are not reported in biophilic design studies. Therefore, there is potential for further research in this area.
Biological responses (Physiological responses Psychological responses Cognitive responses)	Collecting human physiological, psychological, and cognitive data is possible in VE, especially in human-related studies. For quantifying human's physiological responses to biophilic environments, there are a variety of wearable bio-monitoring sensors, such as heart rate (HR), heart rate variability (HRV), blood pressure (BP), and skin conductance level (SCL). In addition, due to technology advancements, researchers can apply eye-tracking technology (e.g., Tobii Pro), which monitors participant's attention toward specific parts of design during the exposure period (e.g., [26,107]). Regarding psychological and cognitive measurements in VE, the flexibility of VEs for supporting programming and on-screen surveys allows participants to be immersed in VE while providing answers to various psychological and/or cognitive tests [23]. On the other hand, a potential issue is the clumsiness of wired devices that can impact VE experiments. Therefore, streamlined apparatus is preferable [165]. Another challenge is that participant's biological responses and task performance can be affected due to VE platform or display methods [166]. Furthermore, possible cybersickness may also negatively impact the user's task performance and biological responses.	Eye-tracking technology in combination with VE and bio-monitoring sensors is an effective research tool for biophilic design [32].

Table 2. *Cont.*

Parameters of Biophilic Design Studies	General VE Capabilities and Limitations	VE Application for Biophilic Design Studies
Stress induction **Mental fatigue**	As mentioned above, on-screen tests and programming in VEs enable scholars to create various tests, including mental fatigue tests in VEs. Moreover, increasing stress-inducing tasks is also reported in the literature. For example, VR-Trier Social Stress Test (TSST) is a confirmed tool in stress research (e.g., [149,167]).	According to the two fundamental biophilic theories, Attention Restoration Theory (ART) and Stress Recovery Theory (SRT), in many biophilic studies, researchers consider stress induction or mental fatigue through different tests and tasks. VR-TSST is stress inducing task in VE that also has been reported in biophilic studies (e.g., [130,168]). Therefore, VE can create stress induction required for some biophilic studies.
Natural environment setting (Indoor and outdoor built environment Urban space Wild nature)	The modeling and programming capability of VE software such as Unity and Unreal Engine as well as 360-degree videos or panoramic images of a real environment support researchers to create or represent various natural environmental settings in VE (e.g., [33,34,120,124,135,137]).	Various natural environment settings in VE are reported in the literature, including empirical studies on the indoor environment (e.g., [31,33]), outdoor environment such as shopping mall plaza (e.g., [51]), large scale urban park (e.g., [23,169]), etc. There is a limited number of studies that quantify the physiological and cognitive benefits of indoor biophilic elements and patterns. It is recommended to also apply virtual biophilic environment stimulation to other indoor settings, such as education, housing, recreation, and retail
VE Sensory inputs (Visual Auditory Olfactory Tactile Thermal **and** wind)	VE supports visual, auditory, olfactory, tactile inputs. As mentioned, realistic experience in VE and, consequently, successful application of VE depends on sensory fidelity, auditory, olfactory, and other sensory cues similar to reality [170]. Realistic experience in VE, high level of immersion, and presence are related concepts that have been explored over the years. For example, in [82], a multimodal VE via visual, auditory, tactile, olfactory stimuli is provided. However, technically, there are still limitations for generating auditory output in real-time with dynamic changes [63], for example. In addition, haptic stimulation is possible but in a restricted domain of applications.	Diverse combinations of sensory stimuli have been studied for biophilic design in VEs. As mentioned above, non-visual connection with nature is a biophilic design pattern. It is recommended to design for simultaneous visual and non-visual connections to nature [7], which increase positive health impacts and facilitate stress reduction. Therefore, sensory inputs improve immersion and the individual's presence in VE, which contributes to biophilia and biophilic design. Although there are some research studies with multimodal cues (e.g., [123,125,137,168]), most studies incorporate only auditory and visual cues. To illustrate, an actual biophilic environment like a forest incorporates five senses as well as air, temperature, humidity, etc., while most VE studies only focus on visual and auditory stimulation. Therefore, there are opportunities to stimulate and engage the more senses in VE and further study individuals' biological responses in relation to biophilic theories, immersion, and presence.
VE validation **VE presence** (Single user vs. multi-user)	Similar results and effects in exposure to virtual vs. actual natural environment are reported in the literature (e.g., [31,92,171]). Under controlled laboratory circumstances, VEs can provide more immersive experiences and more realistic physiological responses, comparing to mediated environments [172]. Regarding VE presence, the majority of the studies are designed for a single user, although multi-user experiments are technically possible.	Empirical studies show consistent biological responses to biophilic design in the real-world and 360-degree video in VE (VE validation) [31]. However, in a study [33], cognitive performance in biophilic design in VE is not consistent with that in-situ. More studies are required.

Table 2. *Cont.*

Parameters of Biophilic Design Studies	General VE Capabilities and Limitations	VE Application for Biophilic Design Studies
Subjects and **sample size**	The sample size in most VE studies are small, e.g., less than 200 [93]. Regarding subjects in different domains, scholars have studied participants with a diverse range of ages and backgrounds in VEs.	To be able to generalize research results to the general population, it is necessary to include a variety of participants with representative samples. For example, individual differences, such as gender, childhood experiences, have an impact on participant's responses to biophilic environments and biophilic design (e.g., [9,23,32]). Moreover, currently, most research studies include healthy users; there are very few studies on users with physical or cognitive impairment (e.g., [121,122,143,173]). More in-depth research is recommended in order to explore virtual biophilic environment's impact on individuals with different demographic characteristics and backgrounds.
Exposure duration	VE research studies typically have short experiment sessions to avoid possible issues, such as cybersickness.	Based on empirical research, effective exposure to biophilic environments for stress reduction, positive emotions, and restoration can be 5 to 20 min [7]. Therefore, VE, specifically VR technology, is capable of supporting the required exposure time for effective biophilic studies.

7. Conclusions

In this paper, a literature review of biophilic design and VE is carried out to understand their concepts and main features. In addition, the research identifies key elements required for virtual natural environments studies and proposes important factors contributing to the design of biophilic environment experience in VE. Furthermore, the paper discusses VEs' applications, capabilities, and limitations for biophilic design, as well as some potential research directions.

Specifically, the literature review shows that three categories of biophilic design are reported; however, natural elements are the most repeated category due to their familiarity with users and ease of implementation. In addition, a variety of biophilic patterns, especially visual and non-visual connections to nature, are studied in VE. According to the two prominent biophilic theories, ART and SRT, most studies considered stress induction or mental fatigue tasks as well as virtual biophilic recovery in their experimental procedure. VE enables scholars and designers to create effective exposure time (5–20 min) to the virtual natural environment for stress reduction, positive emotion and mood, and restoration. It also supports creating different tests and tasks and collecting real-time data while individuals are immersed in the virtual natural environment. To this end, it allows researchers to collect user's physiological, psychological, and/or cognitive responses to virtual stimuli.

The literature reveals that immersion in virtual natural environment has the potential to produce similar positive outcomes of exposure to nature. In other words, VE can replicate positive physiological, psychological, and cognitive responses of participants to an environment with natural elements. Furthermore, empirical studies prove the restorative properties and stress reduction potential of VE experience when it includes biophilic patterns and virtual natural elements. Consequently, it can provide a realistic representation of a natural environment and supports the ecological validity of VE for biophilic design. Between 3D stimulated VE and mediated environments, simulated VE represents virtual nature with higher immersion, maximizes the sense of presence and realism, and provides higher ecological validity for research. Higher immersion and presence in VE have impact on the individual's psycho–physiological and cognitive responses and improves the restorative potential of the virtual biophilic environment.

Based on reviewed studies in the literature, most VE users are mentally and physically healthy, and there are only a few studies investigating the impact of virtual natural environment on users with cognitive or physical impairment. Regarding the impact of virtual biophilic environments on individuals, many factors, such as age, gender, childhood experience, and familiarity with technology are influential and need to be further studied.

Moreover, VE is capable of representing outdoor and indoor biophilic built environment as well as wild nature, such as a forest. However, there is a limited number of empirical research studies on biophilic design in built environments, which explore human responses to natural elements. In addition, the literature shows that adding sensory stimuli improves the sense of reality and presence and influences participant's physiological and behavioral responses. It can also result in more restorative environments or more efficient recoveries in VEs. However, the literature shows that most studies incorporate only visual and auditory stimuli. Therefore, adding other sensory factors to improve individual's presence in virtual biophilic environment, while avoiding their possible cybersickness, can be further studied in the future.

The literature review shows there are many research opportunities with respect to biophilic design patterns, biological responses of users, and sensory input. For example, the approach to model natural analogues and the experience of space and place, the second and third categories of biophilic design, is not fully understood. More research is also needed to better understand the relationship between stress reduction and participants' attention in virtual environments. In addition, many experimental protocol details still need to be verified under different scenarios, such as the exposure time to biophilic elements in virtual environments. Other opportunities also exist with respect to improvements in VE and its applications in general, such as improvements in immersion and presence, as well as sensory input.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Classification of the reviewed studies employing virtual natural environment (factors 1–4).

Literature	Biophilic Categories and Patterns									Biological Responses			Collected Data		
	Natural Elements				Natural Analogues			Experience of Place and Space		Stress Reduction	Emotion, Mood and Preference	Cognitive Performance	Physiological Data	Psychological Data	Cognitive Data
	Visual	Non-Visual	Light	Thermal and Airflow	Material	Shapes and Forms	Patterns and Processes	Human–Nature	Place-Based						
[34]	*		*		*	*				*			*	*	
[33]	*		*		*					*	*	*	*	*	*
[119]	*	*	*					*			*		*	*	
[120]	*	*									*			*	
[121]	*	*	*							*	*		*	*	
[122]	*	*	*							*	*			*	
[32]	*		*		*	*				*	*	*	*	*	*
[123]	*	*	*								*			*	
[124]	*		*					*		*	*		*	*	
[125]	*	*								*	*		*	*	
[126]	*	*						*		*		*	*		*
[127]	*		*							*	*	*	*	*	*
[128]	*		*								*			*	
[31]	*		*		*					*	*	*	*	*	*
[22]	*	*	*							*	*		*	*	
[129]	*	*	*							*	*		*	*	
[23]	*							*			*			*	
[130]	*	*								*	*		*	*	
[131]	*		*							*				*	
	*		*							*				*	
[51]	*		*								*			*	
[132]	*		*							*	*		*	*	
[19]	*	*	*								*	*		*	*
[21]	*	*	*						*		*			*	

Table A1. *Cont.*

Literature	Biophilic Categories and Patterns									Biological Responses			Collected Data		
	Natural Elements				Natural Analogues			Experience of Place and Space		Stress Reduction	Emotion, Mood and Preference	Cognitive Performance	Physiological Data	Psychological Data	Cognitive Data
	Visual	Non-Visual	Light	Thermal and Airflow	Material	Shapes and Forms	Patterns and Processes	Human–Nature	Place-Based						
[133]	*	*	*	*						*	*		*	*	
[134]	*		*							*		*	*		*
[135]	*	*	*					*		*				*	
[136]	*	*	*							*			*		
[137]	*	*	*							*	*			*	
	*	*	*							*	*		*	*	
[138]	*	*										*			*
[139]	*	*	*							*	*	*	*	*	*
[140]	*	*	*							*	*	*	*	*	*
[143]	*		*							*			*	*	
[20]	*		*								*	*		*	*
[141]	*		*							*		*	*		*
[142]	*		*								*	*		*	*
[113]	*		*							*	*		*	*	

Table A2. Classification of the reviewed studies employing virtual natural environment (factor 4—data collection and measurements).

Literature	Measurements		
	Physiological Data	Psychological or Cognitive Data	VE Validation Data
[34]	heart rate (HR), heart rate variability (HRV), skin conductance level (SCL), blood pressure (BP)	State-Trait Anxiety Inventory (STAI)	
[33]	HR	Working memory tests (Cog: color and shape); Positive and Negative Affect Schedule (PANAS) (mood),	Igroup Presence Questionnaire (IPQ)
[119]	SCL	PANAS (mood), perceived restorativeness scale (PRS) (restorativeness), DSS, EBS (disgust and beauty of nature)	

Table A2. *Cont.*

Literature	Measurements		
	Physiological Data	**Psychological or Cognitive Data**	**VE Validation Data**
[120]		Summary of Positive and Negative Experiences (SPANE) (mood), Multidimensional State Boredom Scale (MSBS) (boredom), Inclusion of Nature in Self Scale (INS)	Presence and Judgment Questionnaire
[121]	HR	PANAS (mood), Overall mood assessment	
[122]		STAI (anxiety), Music in Dementia Assessment Scales (MiDAS) (mood), Observation	VE Experience Questionnaire
[32]	BP; HR; HRV; SCL	Cog: Stroop test (color-word); Guilford's Alternative Uses (AU test); Eye tracking; PSY: self-reported preference to biophilic patterns	
[123]		NSR (pleasantness of window view); PRS; Nitsch's Personal State Scale (mood, fatigue, and arousal)	
[124]	HR, BP, Salivary Amylase	Brief Profile of Mood States (BPOMS)	
[125]	SCL	Perceived Pleasantness	
[126]	HR, HRV, SCL	Digit Span Backwards (DSB), Necker Cube Pattern Control (NCPC) (attention and memory)	
[127]	Electroencephalogram (EGG)	Profile of Mood States (POMS-SF) (stress), Cog: Stroop color task	
[128]		PANAS, 8 Emotion	ITC- Sense of Presence Inventory (ITC-SOPI)
[31]	HR; SCL; BP	Cog: visual reaction time task; visual backward digit span task; Stroop task; PSY: self-reported emotion changes	
[22]	walking speed; HR;	Perceived Environmental Restorativeness (PER); Physical Activity Affect Scale (PAAS); Ratings of Perceived Exertion (RPE); enjoyment scale; perceived motivational effect; open-ended questions	Presence scale
[129]	Systolic Blood Pressure (SBP); HR; Salivary α amylase activity (activity of the sympathetic nervous system)	POMS (profile of mood state)	
[23]		PRS; Perceived Safety (PS)	
[130]	Stress and emotion: HRV; salivary cortisol	STAI; PANAS	IPQ (presence); Game Experience Questionnaire (immersion)

Table A2. *Cont.*

Literature	Measurements		
	Physiological Data	**Psychological or Cognitive Data**	**VE Validation Data**
[131]		Numeric Rating Scale (NRS) for pain experience; McGill Pain Questionnaire (SR-MPQ); NRS recalled pain at 1week follow-up	
		Modified Dental Anxiety Scale (MDAS); NRS pain experience; NRS for stress (From the Profile of Mood States); PRS; NRS recalled pain	SR based on IPQ, reality judgement and presence Q
[51]		PRS	
[132]	HRV; HR; Near-Infrared Time-Resolved Spectroscopy (TRS)	Subjective feeling measured with SD method (semantic differential method)	
[19]		Biophilic Attitudes Inventory (BAI); PANAS; PRS; Cog: Attention Network Test (ANT); Proof Reading Task (PRT); Digit-span test; Compatibility task;	
[21]		PRS; PANAS; Depression Anxiety Stress Scales (DASS-21)	
[133]	HRV, Electrodermal activity (EDA)	PANAS	Modified Reality Judgement and Presence Questionnaire (MRJPQ)
[134]	Vital monitoring system	Cog: use Eye-tracker	IPQ, Presence Questionnaire (PQ), System Usability Scale (SUS), Simulator Sickness Questionnaire (SSQ)
[135]		PRS; observation; semi-structured interview	
[136]	HR, HRV, T-wave amplitude; saliva cortisol; subjective		Short scale (sense of presence)
[137]		NSR (Anxiety and Relaxation)	VE System usability (hand-controller and navigation)
	HR; SCL	NSR (odor and preference)	
[138]		Cog: Trail Making Task (TMT), Controlled Oral Word Association Test (COWA) (attention)	
[139]	HR; SCL	Zuckerman Inventory of Personal Reactions (ZIPERS); PSY: mental-arithmetic quiz	IPQ
[140]	HR; SCL	Cog: Sustain Attention to Response Task (SART); ZIPERS; Self Report stress	Simulator Sickness Questionnaire

Table A2. *Cont.*

Literature	Measurements		
	Physiological Data	Psychological or Cognitive Data	VE Validation Data
[143]	Pulse; SBP; DBP	Self-estimated level of current stress; Emotional state test; Stress and energy test (SE); Experienced Deviation from Normal state (EDN); mental fatigue: Syllogism I–II	
[20]		Semi-structured interview; work satisfaction, office perception, and mood surveys; responses to email queries; journal entries;	
[141]	HR; IBI;	Camera; PRT; name-a-Droodle" task; "invent-a-Droodle" task; "tin can unusual uses" task	
[142]		PANAS; Cog: backwards digit- span task; ANT	
[113]	HR (inter beat interval, IBI); SCL	Affect questionnaire based on PANAS and ZIPERS	ITC-SOPI

Table A3. Classification of the reviewed studies employing virtual natural environment (factors 5–7).

Literature	Subjects		Stress or Mental Fatigue Induction				Natural Environment Setting/ Context			
	Healthy	Patient	Pre-Exposure	Peri-Exposure	Post Exposure	None	Biophilic Indoor Environment	Biophilic Outdoor Environment	Urban Green Space or Streetscape	Wild Nature
[34]	*		*				*			
[33]	*			*	*		*			
[119]	*					*				*
[120]	*		*							*
[121]		*				*				*
[122]		*				*				*
[32]	*			*	*		*			
[123]	*		*						*	
[124]	*		*							*
[125]	*			*					*	*
[126]	*		*		*					*

Table A3. *Cont.*

Literature	Subjects		Stress or Mental Fatigue Induction				Natural Environment Setting/ Context			
	Healthy	Patient	Pre-Exposure	Peri-Exposure	Post Exposure	None	Biophilic Indoor Environment	Biophilic Outdoor Environment	Urban Green Space or Streetscape	Wild Nature
[127]	*		*		*				*	
[128]	*					*				*
[31]	*			*	*		*			
[22]	*					*			*	
[129]	*		*							*
[23]	*					*			*	
[130]	*		*							*
[131]	*			*						*
	*			*					*	*
[51]	*					*		*		
[132]	*					*				*
[19]	*		*		*					*
[21]	*					*			*	*
[133]	*		*							*
[134]	*					*				*
[135]	*					*				*
[136]	*		*							*
[137]	*					*				*
	*					*				*
[138]	*			*			*			
[139]	*		*		*					*
[140]	*		*		*					*
[143]		*	*							*
[20]	*					*	*			

Table A3. *Cont.*

Literature	Subjects		Stress or Mental Fatigue Induction				Natural Environment Setting/ Context			
	Healthy	Patient	Pre-Exposure	Peri-Exposure	Post Exposure	None	Biophilic Indoor Environment	Biophilic Outdoor Environment	Urban Green Space or Streetscape	Wild Nature
[141]	*		*	*	*		*			
[142]	*		*		*					*
[113]	*		*							*

Table A4. Classification of the reviewed studies employing virtual natural environment (factors 8–11).

Literature	Delivery Mode					VE System				VE Presence		Sensory Inputs				
	Simulated	Mediated														
	Virtual 3D Model	360° Video	2D Video	360° Photo	Static Image	Fully Immersive (HMDs or CAVEs)	Partially Immersive, Projectors	Non-Immersive, Screen	None	Single-User System	Multi-User System	Visual	Auditory	Olfactory	Tactile	Thermal and Wind
[34]	*					*				*		*				
[33]	*		*			*				*		*				
[119]		*				*				*		*	*			
[120]		*	*			*			*	*		*	*			
[121]			*						*	*		*	*			
[122]		*				*				*		*	*			
[32]	*					*				*		*				
[123]			*						*	*		*	*	*		
[124]		*				*				*		*				
[125]				*		*				*		*	*	*		
[126]			*						*	*		*	*			
[127]				*		*				*		*				
[128]		*				*				*		*				
[31]		*				*				*		*				
[22]		*				*				*		*	*			
[129]		*				*				*		*	*			
[23]				*		*				*		*				
[130]	*					*			*	*		*	*			

Table A4. *Cont.*

Literature	Delivery Mode					VE System				VE Presence		Sensory Inputs				
	Simulated	Mediated														
	Virtual 3D Model	360° Video	2D Video	360° Photo	Static Image	Fully Immersive (HMDs or CAVEs)	Partially Immersive, Projectors	Non-Immersive, Screen	None	Single-User System	Multi-User System	Visual	Auditory	Olfactory	Tactile	Thermal and Wind
[131]	*					*				*		*				
	*					*				*		*				
[51]	*								*	*		*				
[132]					*				*	*		*				
[19]					*				*	*		*	*			
[21]			*						*	*		*	*			
[133]		*				*				*		*	*			*
[134]			*			*				*		*	*			
[135]	*							*		*		*	*			
[136]	*					*				*		*	*			
[137]	*							*		*		*	*			
	*							*		*		*	*	*		
[138]			*						*	*		*	*			
[139]	*					*				*		*	*	*	*	
[140]	*					*				*		*	*			
[143]					*				*	*		*				
[20]			*						*	*		*				
[141]			*						*	*		*				
[142]					*				*	*		*				
[113]					*				*	*		*				

Table A5. Classification of the reviewed studies employing virtual natural environment (factors 12–16).

Literature	Research Design															
	Design		Natural Elements Presentation		Sample Size				Duration of Exposure to Each Condition					Total Duration of Each Session		
	Total Settings/Contexts	Total Conditions	Reality vs. Virtual Environment	Virtual vs. Virtual Environment	Less than 20	20–50	51–100	Over 100	Less than 10 min	10–20 min	21–60 min	More than One Hour	More than One Day	Less than Two Hours	More than Two Hours	More than One Day
[34]	1	4		*			100		6					*		
[33]	2	4	*	*		35			5					*		
[119]	2	3	*				*		*					*		
[120]	1	3		*			96		5					*		
[121]	2	2	-	-		36				10				*		
[122]	1	1	-	-			66		3–10	10–20				*		
[32]	2	8		*		30				13					*	
[123]	2	5		*				122		15				*		
[124]	7	7		*			96		5					*		
[125]	3	3		*				154	3					*		
[126]	1	3		*			60		5					*		
[127]	6	6		*				120	5					*		
[128]	1	2	*			50			5					*		
[31]	2	4	*	*		28				10				*		
[22]	2	3	*	*		26				10				*		
[129]	2	2		*		30			9.5					*		
[23]	2	18		*			87		*					*		
[130]	2	3		*			62		7					*		
[131]	2	3		*			85		4					*		
	3	3		*			70		*					*		
[51]	1	2		*			68			20				*		
[132]	2	2		*	17				1.5					*		
[19]	2	5		*				184		10				*		
[21]	3	3		*				220	2–3					*		
[133]	3	3		*	18					15				*		
[134]	3	3	-	-		37				15				*		
[135]	1	2		*		20			4–7					*		

Table A5. *Cont.*

Literature	Research Design															
	Design		Natural Elements Presentation		Sample Size				Duration of Exposure to Each Condition					Total Duration of Each Session		
	Total Settings/Contexts	Total Conditions	Reality vs. Virtual Environment	Virtual vs. Virtual Environment	Less than 20	20–50	51–100	Over 100	Less than 10 min	10–20 min	21–60 min	More than One Hour	More than One Day	Less than Two Hours	More than Two Hours	More than One Day
[136]	2	3		*		30					40			*		
[137]	2	4		*	14				5					*		
	1	3		*	14				3					*		
[138]	1	2	*			40				20				*		
[139]	2	2		*		22				10				*		
[140]	3	3		*			69			10				*		
[143]	1	2	*		18						30			*		
[20]	2	2	-	-	7								6-weeks			*
[141]	2	3	*				90				35			*		
[142]	2	2		*		38				10				*		
[113]	1	2		*			80			10				*		

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