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Heart rate variability in biophilic design: A systematic literature review

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Abstract

The use of Virtual Reality as a representation of biophilic design has been commonly used for design evaluations on human perception and performance before the actual construction. Biophilic design is known for the relaxing effects on human physiological responses; particularly cardiac activity indexed by Heart Rate Variability (HRV), representing human's relaxation or stress conditions. How virtual biophilic design affects HRV, and what research protocols are most effective in assessing these physiological effects remains unclear. This literature review clarifies research protocols and outline the trends of HRV in virtual biophilic design and to propose guidelines for improving the accuracy and reliability of HRV measurements. Most of the reviewed studies found an equal trend of the increased parasympathetic activity correlating with a reduced anxiety, during exposure to specific virtual biophilic designs. Studies with insignificant HRV effects may be due to the inadequate measurement protocol. The clearer effects on HRV may be observed by limiting virtual exposure to 15 minutes, avoiding virtual sickness, maintaining consistent subject positions, incorporating paced breathing in all conditions during HRV recordings, and evaluating short-term HRV measures for a minimum of 5 minutes. Virtual biophilic exposure holds promise for pre-construction design assessment, depending on appropriate methodologies.

Keywords: *biophilic design, nature exposure, virtual stimuli, heart rate variability, physiology*

1. Introduction

Designers are responsible for determining the impact of design in society. Approximately 80% of a product's environmental impact is determined during the early stages of research and development, where designers decide on the materials to be used. (Gumulya, 2023) However, designers' responsibilities extend beyond environmental considerations. A well-designed space using natural, eco-friendly materials can have relaxing and restorative effects on its inhabitants. These environments can enhance mental well-being, reduce stress, and improve overall quality of life. Thus, designers are not only pivotal in promoting sustainability but also in fostering living spaces that support the physical and psychological health of users.

Biophilic design and nature exposure have become a new approach to bringing positive experiences from nature into the design of artificial environments (Kellert et al., 2011). It aims to strengthen the personal connection with nature by integrating natural elements into the built environments of our living and working spaces. Previous study (Justice, 2021) have shown that biophilic architecture design aimed to enhance quality of life through green spaces, impacting both physiological and psychological health and well-being. However, this study did not include a post-occupancy evaluation to objectively measure physiological performance.

The human body responds to its environment subtly yet profoundly, and physiological data offer a window into these responses. Physiological data, particularly cardiac activity indexed by heart rate variability (HRV), play a pivotal role in unravelling the intricate relationship between nature exposure and the human health (Yin et al., 2018). Stress reduction or relaxation, in the physiological field, is closely linked to the autonomic nervous system, comprising the sympathetic nervous system (SNS) and the parasympathetic nervous system (Shaffer & Ginsberg, 2017)(Kartika et al., 2019), which can be measured through heart rate variability (HRV). HRV, the variation in time between successive heartbeats, is a sensitive indicator of the autonomic nervous system's functioning, reflecting the balance between sympathetic (fight-or-flight) and parasympathetic

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(rest-and-digest) activities (Shaffer & Ginsberg, 2017).

Enhanced parasympathetic activity is correlated with relaxation and positive emotions, indicating the low effort of the physiological mechanism. High frequency (HF) HRV is generally considered a valid parasympathetic marker (Rajendra Acharya, U and Paul Joseph, K and Kannathal, Natarajan and Lim, Choo Min and Suri, 2006). However, it is more strongly affected by breathing depth and frequency. In contrast, time-domain markers like the root mean square of successive differences (RMSSD) are less prone to distortion from breathing (Shaffer & Ginsberg, 2017), or body posture changes and are also viewed as indicators of cardiac vagal tone (Laborde et al., 2017). RMSSD offers a reliable reflection of PNS activity (Rajendra Acharya, U and Paul Joseph, K and Kannathal, Natarajan and Lim, Choo Min and Suri, 2006)(Shaffer & Ginsberg, 2017). In stress management, cardiac vagal tone is crucial for various self-regulatory mechanisms encompassing cognitive, affective, social, and health-related aspects (Laborde et al., 2017).

On the other hand, heightened sympathetic nervous system (SNS) activity is linked to stress, anxiety, and the fight-flight response (Shaffer & Ginsberg, 2017). Low frequency (LF) HRV is a marker for the SNS activity (Rajendra Acharya, U and Paul Joseph, K and Kannathal, Natarajan and Lim, Choo Min and Suri, 2006). Stress reduction often involves low SNS states. Since the SNS and PNS are not strictly reciprocal Fields (Berntson, Gary G., and Cacioppo, John T. Field (Berntson, Gary G and Cacioppo, John T and Quigley, 1993). The PNS and SNS activity influences LF power, whereas HF power is primarily associated with PNS activity. The LF/HF ratio suggests that the SNS may contribute to LF power, whereas HF power is attributed to the PNS. Thus, a low LF/HF ratio indicates a PNS dominance (Shaffer & Ginsberg, 2017). In addition, the standard deviation of the interbeat interval (IBI) of normal sinus beats (SDNN) serves as a common measure reflecting both parasympathetic (PNS) and sympathetic (SNS) nervous system activation. The abovementioned norms of HRV are the common HRV markers used in reviewed papers.

A preoccupancy evaluation assesses psychological and physiological responses to biophilic design, refining strategies before construction. Empirical studies conducted in actual natural settings are invaluable, but their prohibitive costs often present formidable challenges. These limitations necessitate innovative approaches that can replicate the benefits of natural exposure without the financial burden. The use of Virtual Reality as a representation of biophilic design in indoor spaces allows for the evaluation of design on human perception and performance before construction takes place. Virtual Reality (VR) presents a compelling alternative to conducting research in natural environments, particularly when studying physiological stress responses. However, it's important to acknowledge that the validity of using VR to study physiological data is a subject of ongoing debate within the scientific community (Weibel, Raphael P and Grubel, Jascha and Zhao, Hantao and Thrash, Tyler and Meloni, Dario and Holscher, Christoph and Schinazi, 2018).

Virtual biophilic design holds potential for influencing HRV and assessing stress or relaxation responses. However, the physiological reactions observed in virtual environments may not fully replicate those experienced in real-world settings. Factors such as the lack of physical elements, altered sensory cues, and the awareness of being in a virtual space introduce complexities that challenge the direct application of findings to real-life scenarios. These discrepancies make it difficult to conduct and interpret physiological research within virtual environments. Therefore, while virtual reality (VR) offers an innovative and cost-efficient method for studying physiological stress, researchers must carefully account for its limitations to improve the reliability and validity of their findings.

Research problem addressed in this literature review is that how virtual biophilic design affects heart rate variability (HRV), and what research protocols are most effective in accurately assessing these physiological effects in virtual environments remains unclear. Given the importance of virtual reality for the assessment of physiological response, there is a need for a systematic review of the relevant literature to examine the measurement method. A systematic literature review (SLR) is a rigorous and comprehensive method of reviewing existing literature to identify relevant studies, analyze data, and synthesize evidence to inform practice and policy (Okoli & Schabram, 2012). By conducting an SLR, the designers, built environment professionals, and researchers can gain a deeper understanding of the benefits and methods of physiological studies by using virtual reality and develop more effective design strategies for built environments, and support sustainable development.

Riches et al., (Riches et al., 2021) conducted a systematic review of virtual relaxation interventions; they found a successful increase in relaxation in most studies yet did not specifically conclude their impact on the autonomic nervous system. In contrast,

Gaertner et al., (2023) specifically examined studies using HRV as an indicator of the autonomic nervous system to assess the efficacy of virtual relaxation interventions. While this study shows promising results, they excluded paced breathing studies to isolate the influence of the virtual environment alone and included subjects with clinical conditions. However, the paced breathing is closely related to the breathing depth and frequency, which contributes to the measures of HF indicating parasympathetic activity or relaxing state. HRV is also affected by the clinical conditions of subjects. To evaluate the basic effects of HRV without interference with clinical conditions, in this review, we focused on the effects of a virtual biophilic environment or nature scenes on the response of HRV in healthy subjects, without excluding the pace-breathing study. The search for relevant literature was conducted using several academic databases, including Scopus, PubMed, and Google Scholar. The search included studies published between 2013 and 2023 investigating heart rate variability responses to virtual biophilic design stimuli on healthy subjects.

This literature review aims to examine research protocols and highlight the trends of heart rate variability (HRV), as the index of human physiological stress, in virtual biophilic designs, as well as propose guidelines for improving the accuracy and reliability of HRV measurements in these settings. It seeks to provide insights into how these methods contribute to understanding the relationship between nature exposure and human well-being. This review serves as a valuable resource for various stakeholders, including designers, built environment professionals, and researchers. Its primary objectives are critically assessing the measured HRV and methods within virtually simulated environments

2. Method

In this article, the selection of reviewed studies was based on the following criteria: (1) The article must be included in the keyword search related to heart rate variability in virtually simulated biophilic environments. (2) The articles were published between 2013 - 2023 to ensure the inclusion of the most current research in the field. (3) The article must be indexed in all the following databases: Scopus, PubMed, and Google Scholar. (4) The article must an original article that clearly present the methods and results of heart rate variability measurement under virtually simulated biophilic environments. (5) The article must include healthy subjects to assess HRV effects without the interference of clinical conditions. The activities of subjects are also limited to a sedentary position to eliminate the variation effects of physical working loads.

The ROSES review Protocol, "RepOrting Standards for Systematic Evidence Syntheses," is employed in this literature review. The ROSES methodology has the potential to be applied to other sectors facing issues and procedures of comparable complexity (Haddaway et al., 2018). We performed a systematic search procedure, encompassing tasks such as locating, screening, and establishing exclusion and inclusion criteria for the articles. Identifying, Filtering, and Determining the eligibility of articles are the procedures used in this study's search approach. This article employed four steps of article selection as described in Figure 1.

The search criteria included keywords related to heart rate variability in virtually simulated biophilic environments. The search was restricted to peer-reviewed articles published between 2013 and 2023 to ensure the inclusion of the most up-to-date research in the field. Advanced search features, including Boolean operators, phrase search, truncation, wild cards, and field code operations, were employed to broaden and refine the search procedures. These options were available in Scopus and PubMed databases. Google Scholar was included as an additional database search, as a supplementary resource for the systematic review process due to its exceptional results compared to other databases (Haddaway et al., 2018). However, it should be noted that Scopus and PubMed databases do not include all studies from the perspective of the physiological anthropology field. **Error! Reference source not found.** lists the search keywords applied to the various databases.

All databases utilized in the identification processes yielded a total of **237 articles**. The selection of article is limited to the article that is indexed on all these databases (Scopus, PubMed, and Google Scholar) ensuring the quality and relevancies of the study. After finding repetitive content in these databases, in total of 14 articles from these three databases were reviewed.

The next action is screening the search results. Selected papers were read in the first stage after only reading their abstracts, and the complete contents of those articles were read in the second stage. The article should be an original article that clearly presents the methods and results of heart rate variability measurement under virtually simulated biophilic environments. After screening, 12 articles met the criteria for the screening phase.

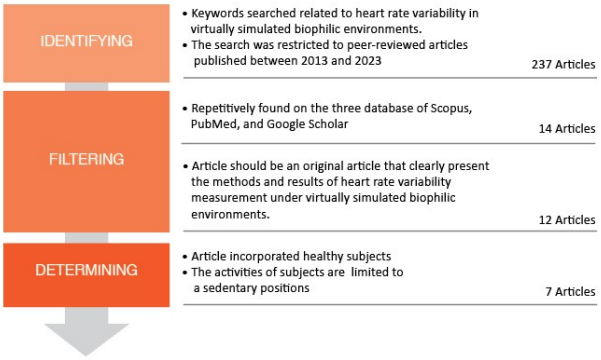

Figure 1. Selection Scheme

Table 1 Search String in the advanced search of databases

Database	Search String
Scopus	TITLE-ABS-KEY (("heart rate variability" OR "HRV") AND ("virtual" OR "virtual reality" OR "virtual environment" OR "virtual stimuli" OR "Virtually simulated") AND ("biophilic" OR "nature"))
PubMed	Title/Abstract (("heart rate variability" OR "HRV") AND ("virtual" OR "virtual reality" OR "virtual environment" OR "virtual stimuli" OR "Virtually simulated") AND ("biophilic" OR "nature"))
Google Scholar	All abstract all title "heart rate variability" AND "virtual environment" OR "virtual stimuli" OR "virtually Simulated" AND "biophilic" OR "nature"

Throughout the comprehensive reading of the text, remarks on heart rate variability contents relevant to the study's aims and scope were highlighted, specifically on sedentary activity. The full-text article screening also excluded studies employing subjects with clinical disease and conducting non-sedentary positions, which may alter the response to cardiac activity. Following the eligibility check, the total number of academic articles retained was 7 articles. Following the paper's selection, the data undergoes evaluation and summarization to identify common themes and key findings. The summarized findings highlight common themes and major discoveries. Ultimately, the implications of these findings for heart rate variability in virtually simulated biophilic environments are concluded and discussed.

3. Results and discussion

This systematic review aimed to examine the calming impacts of virtual natural exposure or biophilic environments, employing heart rate variability (HRV) as an indicator of parasympathetic nervous system (PNS) activity. Herein, we classified each paper according to the type of nature stimuli investigated in each manuscript, namely: natural scenes and indoor biophilic. Among the 7 reviewed papers, three studies incorporated natural scenes and others used indoor biophilic. Effects on others physiological data and subjective response were summarized within the subgroups.

In general, the findings from these studies revealed relaxing effects in HRV, as evidenced by diverse HRV markers, although the effects of stimuli given were not significantly observed. A list of the included studies is shown in **Error! Reference source not found.**. We discuss below, in separate sections, the papers on natural scenes and indoor biophilic, as per the structure outlined above.

Effects of Virtually Simulated Natural Scenes on HRV

Among the 7 included studies, four studies used natural scenery as virtual stimuli for the participants. These studies find statistically significant results on the relaxing effect on HRV in between time or between conditions. They present a similar trend of relaxing effects during the exposure of VR Nature Scenery.

Anderson et al (Anderson et al., 2017) exposed subjects to three conditions; empty indoor classrooms as a baseline, natural scenes or Ireland with views of water, animals, houses and roads, and conditions of natural scenes of beach with ocean sounds, and soothing music, with 2 minutes of Arithmetic test as the stressor before exposure of VR. The VR exposures were last for 15 minutes with different subjects' position during HRV measurement; seated position on classroom and Ireland natural scenes condition, and supine position is allowed for the beach condition. They observed significantly decreased HF initially during stress and increased as subjects relaxed with virtual reality (VR) in all conditions.

The LF/HF ratio and Skin conductance level were elevated during the stress test and gradually decreased over time during the VR experience. but no significant difference between the conditions was found. Among all conditions, only the beach conditions significantly decreased the LF/HF ratio by the end of exposure, compared to the baseline time. Parasympathetic nerve activity increased when exposed to nature sounds compared to urban sounds

(Song et al., 2023). Therefore, this result may be affected by the additional stimuli of ocean sound and allowance of supine position only in this condition, that escalate the relaxing effects.

These results indicate the stressing effect of arithmetic test and the more relaxing effect of viewing virtual nature scenes, but not allow to conclude which elements of natural scenes that more relaxing from the point of view of HRV. In addition, the evaluation of frequency based HRV in this study was based on 2 minutes interval, while the conventional short-term recording period is 5 minutes (Shaffer & Ginsberg, 2017). Also, the unequal subject's position that allowssupine position in one condition may alter the HRV results.

Ho, Wu and Yen, (2023) studied the effects of viewing 360 video of nature scene using head

Tabel 2. List of selected studies in heart rate variability in virtual nature scene or biophilic

Authors	Conditions		HRV Measurements		
	VR stimuli	VR exposure duration per condition	Indexes of HRV	Duration for HRV analysis	Subjects position during HRV measurement
Ho, Wu and Yen, 2023 (Ho et al., 2023)	1. Non treatment, 2. With VR Treatment - Nature 360' video	30 minutes	SDNN, LF HF, LF/HF	5 minutes	Sitting
Schöne et al., 2023 (Schöne et al., 2023)	1. Real life height level 2. PC simulated height level 3. VR simulated height level	63 seconds	SDRR RMSSD	63 seconds	Standing
Anderson et al., 2017 (Anderson et al., 2017)	1. Empty indoor classrooms 2. Natural scenes Ireland: with views of water, animals, houses and roads. 3. Natural scenes of beach: with ocean sounds, and soothing music.	15 minutes	LF HF LF/HF	2 minutes	Sitting in two conditions; Supine in beach condition
Blum, Rockstroh and Göritz, 2019 (Blum et al., 2019)	1. HRV-BF treatment: beach scene 2. VR Based - HRV_BF Treatment: beach scene	not defined	RMSSD	not defined	not defined
You et al., 2023 (You et al., 2023)	1. Non-biophilic 2. Indoor Green 3. Outdoor Green 4. Outdoor green with pollution 5. Indoor and Outdoor Green	3 minutes	RMSSD	3 minutes	Seated during resting phase, Walking during exposure phase
Yin et al., 2020 (Yin et al., 2020)	1. Non Biophilic, 2. Indoor Green, 3. Outdoor View, 4. Combination.	6 minutes	RMSSD LF/HF	30 seconds	Walking and sitting
Yin et al., 2019 (Yin et al., 2019)	1. Non-biophilic, 2. Natural elements, 3. Natural Analogues, and 4. Combination, (in both Enclosed Space and Open Space)	13 minutes	RMSSD	not defined	Walking and sitting

mounted display, once before and once after the 12-week intervention. The stimuli given was 30 minutes with 5 minutes of HRV evaluation, analyzing SDNN, LF, HF, and LF/HF of HRV. Subjects were sitting still during the recording or HRV, they found that subject group with intervention has significantly higher SDNN and HF, than the control group who did not experience the intervention, indicating the relaxing effects of viewing virtual nature scene. Although this study presents the success of stress reduction, the results include responses of some subjects with VR sickness complaints during the 30 minutes of virtual exposure. Another study has focused on the realness effects of virtual reality on HRV and electroencephalogram. Schöne et al., (2023) investigated three conditions of viewing a nature scene from a height level; real-life by using a fire truck, simulated by computer, and simulated by VR. During the highest point of 63 seconds, HRV measurements is recorded. The observed changes of SDRR measure were significantly higher in VR condition and Real-Life condition, compared to the PC, while no significant difference between VR and real life, indicating the increased of stress induced by real-life and virtual reality was not differed.

Blum, Rockstroh and Göritz (Blum et al., 2019) investigated the benefits of using a virtual nature environment to administer immersive heart rate variability biofeedback (HRV-BF) based on slow-paced breathing and evaluates the RMSSD measures. They exposed subjects to a treatment of biofeedback HRV (HRV-BF) by viewing a beach scene on a computer screen compared to beach scenes in VR Based - HRV_BF Treatment, after participating in a Stroop task as a stressor. However, they do not clearly specify the duration used for HRV analysis. Significant difference was found in this study; in VR, using heart rate variability biofeedback (HRV-BF) in a virtual reality setting mitigated the adverse effects of a subsequent stressor. No significant difference between non-VR and VR conditions.

Differences in methodology among these studies pose challenges in comparing their results, encompassing variations in HRV indices, duration of exposure to nature elements, presence or absence of a preceding stressor, and subjects' positions. Consequently, further research is essential to gain a more comprehensive understanding of how psychopathology influences the relaxation response.

Effects of Virtually Simulated Indoor Biophilic Design on HRV

In contrary to that of nature scene that mostly created by video record that played in head mounted display, the virtually simulated indoor Biophilic Design is commonly created through a 3D modelling that is rendered real time by using VR. Biophilic Design comprises of 14 elements (Ryan et al., 2014) that most researchers investigate which are the dominant element affecting human physiological markers.

The influence of five distinct virtual classroom scenes featuring various biophilic elements and turbidity (hazy outdoor view that imitate air pollution) in VR was studied to explore the potential impact of visual stimulations on stress levels and cognitive functions (You et al., 2023). They evaluated RMSSD, blood pressure, heart rate, and skin conductance level. No significant alterations in physiological stress reactions or cognitive functions were observed with the biophilic and turbid interventions in virtual reality (VR). Although, they observed a similar trend of the increased Diastolic Blood Pressure during VR exposure compared to the baseline, indicating the increased of arousal. This study, however, allowed subjects to be seated during resting phase, and walking during exposure phase, which make both phase is incomparable on HRV effects, due to different subjects' position.

Biophilic elements play a significant role in inducing calming effects. In a study by Yin et al. (Yin et al., 2020), subjects were exposed to a two-minute stressor involving memory and arithmetic tests, followed by randomized virtual biophilic environments: Non-Biophilic, Indoor Green, Outdoor View, and a combination of Indoor Green and Outdoor View. The VR exposure lasted for 6 minutes, during which subjects walked for the first four minutes and sat for the remaining two. RMSSD and LF/HF ratio were analyzed at 30-second intervals. The rate of change in RMSSD during the 6-minute exposure was significantly faster in the Indoor Green condition compared to Outdoor View and the combination condition, suggesting that indoor biophilic elements expedite the recovery from physiological stress. No significant differences were observed in the recovery rates of LF/HF ratio, heart rate, and skin conductance level between biophilic and non-biophilic environments. It's important to note that the results include the allowance for walking during HRV evaluation. Effects of biophilic design is observed in a study simulating office setting.

Another prior study by Yin et al., (Yin et al., 2019) assessed virtual stimuli, including non-biophilic, natural elements, natural analogues, and a combination of natural elements and analogues in both enclosed and open spaces. However, this study did not incorporate a stressor before VR exposure.

Each VR session lasted 13 minutes, followed by additional stimuli, resulting in a total of 52 minutes of VR exposure. The findings did not yield a significant difference of RSMSSD between conditions. However, they observed an increasing trend in RMSSD along with significant decreased SCL in enclosed spaces with combinations of biophilic elements and closed spaces with combinations of natural elements. Biophilic design, employed as a strategy for promoting health, has the potential to diminish stress and enhance creativity within office environments. The impact of these effects varies across distinct biophilic interventions and in diverse workspace configurations (open versus enclosed space).

The objective of this systematic review was to explore the calming effects of virtual interventions, utilizing HRV as an indicator of parasympathetic nervous system (PNS) activity, as well as the method behind the obtained results.

Seven studies were incorporated in this review. Overall, the findings from these studies revealed that virtual nature scene or biophilic environments bring a trend of decreased physiological stress as indexed by various HRV measures; RMSSD (Blum et al., 2019; Yin et al., 2019, 2020); SDNN (Ho et al., 2023), SDRR (Schöne et al., 2023), HF (Ho et al., 2023), and LF/HF (Anderson et al., 2017). These studies mostly observed the similar trend of relaxing effect or recovery state during exposure of nature scene or biophilic design, although only some studies found a significant results of HRV measures between time (Anderson et al., 2017; Blum et al., 2019) and between conditions of virtual stimulation (Ho et al., 2023; Schöne et al., 2023; Yin et al., 2020). These studies differed in measured duration of HRV recordings, HRV measurement protocol with pre-stressor or without stressor, and position or activity of subjects during HRV evaluation, and exposure duration of VR, as discussed below.

Duration of HRV recordings

It clearly shows that most of the reviewed article incorporated RMSSD for physiological evaluation. It may be due to the complexity of stimuli tested that only allow them to measure HRV in the short duration (5 minutes or less), also known as Ultra-short-term HRV (Shaffer & Ginsberg, 2017). Comparing stimuli or nature scene or various biophilic elements may takes time, meanwhile the longer the duration of virtual exposure may heighten the risk of motion sickness (Saredakis et al., 2020). Also, the selection of healthy subjects may be the reason of choosing RMSSD as the evaluated measure since the short duration of RMSSD is a promising measure for non-clinical evaluation.

RMSSD, SDNN, SDRR are time based HRV, while HF and LF/HF are frequency based HRV. Both are possible for short-term measurement. The duration of HRV analysis used in the reviewed articles varied. Although the conventional use of HRV analysis for the recorded measures in these articles is 5 minutes, some studies analyze HRV in less than 1 minute (Yin et al., 2020), 1-3 minutes (Anderson et al., 2017; Schöne et al., 2023; You et al., 2023), and 5 minutes (Ho et al., 2023). Many other researchers reviewed in Shaffer and Ginsberg, (2017) proposed to record in a shorter time, those studies faced significant methodological shortcomings. Variations in contextual factors like recording method, age, health, measurement condition, and the validity criteria might exert a more pronounced influence on ultra-short-term measurements compared to longer recordings. Thus, concerning the non-significant results between conditions in almost all the reviewed article, less than 5 minutes duration of HRV analysis may be insufficient for HRV evaluation.

Inclusion of Pre-Stressor

To evaluate the relaxing effects of virtual nature scene or biophilic environments on HRV and to optimize stress induction and prevent potential carry-over effects in a within-subject design experiment, many reviewed studies employed stressor(s) prior to VR exposure. Duration and type of stressors were varied; 2 minutes of Arithmetic (Anderson et al., 2017), 5 minutes of Stroop task (Blum et al., 2019), 2 min Memory and Arithmetic task (Yin et al., 2020). They observed significant results between time, that significantly relaxed effects were observed during VR exposure right after experienced stressor. It indicates the success of VR exposure. However, since they did not find the significant effect between conditions, it may also indicates that the task is strong enough to raise stress that regardless of subsequent natural stimuli, one will consistently experience reduced stress. Interestingly, (Yin et al., 2020) used Memory and Arithmetic test as a pre-stressor and observed significant result of HRV between conditions.

On the other hand, some reviewed studies did not employed pre-stressors (Ho et al., 2023)(Schöne et al., 2023)(Yin et al., 2019)(You et al., 2023), but still achieved a significant difference of HRV measures in between time (Ho et al., 2023) (Schöne et al., 2023). Taken together, stressor prior exposure to VR stimuli is optional when evaluating the relaxing effects of virtual biophilic environments. When pre-stressor is required, Memory and Arithmetic task is

recommended as a pre-stressor, with also a clear design of conditions.

Subjects' activity during HRV measurement

The position of subjects incorporated in the evaluation of HRV is important. The heart rate fluctuates during various physical activities and body positions (sitting, standing, and lying down) (Acharya U et al., 2005). Some measures of HRV are less correlated with respiration such as RMSSD while others are highly correlated (HF). Among 7 studies, 6 allowed subjects to walk freely (Anderson et al., 2017; Yin et al., 2019; You et al., 2023) or changing postures from sitting to supine (Anderson et al., 2017) without specific guidance during the recording of HRV and included into the results . Talking, walking, or even seated or supine position is potential for altering HRV measures due to the altered respiration and metabolic rate. Thus, during measurement of HRV, it is strongly suggested to maintain the equal subject's position in all experiment conditions.

Exposure Duration of VR

VR exposure duration per condition used in this article review is 6 min (Yin et al., 2020), 13 min (Yin et al., 2019), 15 minutes (Anderson et al., 2017), and 30 min (Ho et al., 2023). Among those studies, exposure of 30 min reported virtual sickness. The profiles of VR sickness were affected by visual stimulation, locomotion, and duration of exposure (Saredakis et al., 2020). Studies with exposure times of less than 10 minutes showed lower scores in both nausea and disorientation compared to those with equal to or more than 10 minutes. Intriguingly, scores were even lower for studies with equal to or more than 20 minutes than those with equal to or more than 10 minutes, which also dependent on the VR content itself. In this review, complaints come from VR exposure of 30 minutes with content of nature scene video with seated position, which is the most stable posture. While others did not report any virtual sickness. According to this, VR exposure duration is suggested to be controlled within 15 minutes or less and adjusting the protocol with in-between rest if followed by several stimuli.

The significance of synthesizing the existing literature is found in recognizing methodological challenges and the consistent trends of HRV responses to the virtually simulated Biophilic Designs. The review shows important methodological considerations (Figure 2) that should be considered for further HRV research in virtual environment to avoid confounding factors as follows: (1) Limit virtual exposure to no longer than 15 minutes to avoid

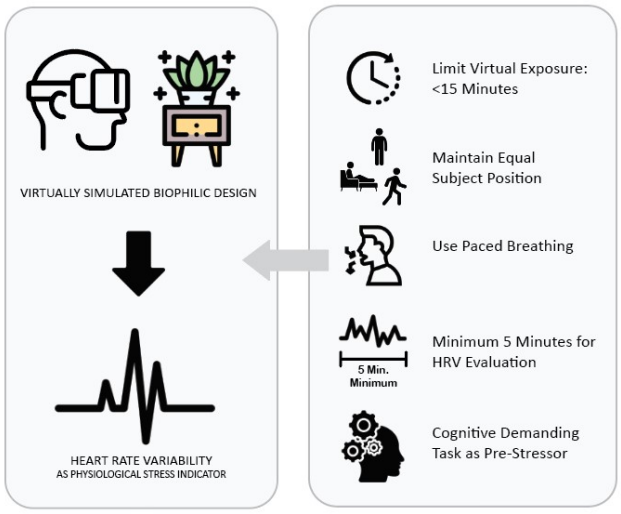

Figure 2 Recommendation of Methodological Consideration on HRV Measurement in Virtual Biophilic Design

the risk of motion sickness. (2) The duration of HRV evaluation should not be less than 5 minutes for data validity. (3) Incorporate the subjects' paced breathing during the measurement of HRV to normalize individual variations. (4) If a pre-stressor is required, an arithmetic task is recommended, as it is sensitive to HRV. (5) Maintain an equal position for the subjects in all experimental conditions, as cardiac activity is sensitive to movement and position.

4. Conclusion

The objective of this systematic review was to explore the effects of biophilic virtual exposure on heart rate variability (HRV) as an index of human physiological stress. Despite notable heterogeneity among studies, the findings indicate that virtual interventions, particularly those incorporating nature stimuli and enhancing the sense of presence, hold promise as relaxation strategies revealing an overall positive influence of biophilic virtual relaxation effects on HRV.

The review compiles findings from seven studies, showing a general trend of decreased physiological stress in response to virtual nature scenes or biophilic environments, as indicated by various HRV measures (e.g., RMSSD, SDNN, HF, and LF/HF). Although, the effects on HRV may be clearly seen with considerations to limit the exposure duration within 15 minutes, control the position of subjects as well as implementing paced breathing in all conditions during

HRV recordings, and evaluate the short term HRV measures in minimum of 5 minutes. In addition to HRV measurements, common stressors used prior to VR stimuli were Arithmetic tasks.

By synthesizing these findings, the review points out areas where research methodologies can be standardized to ensure reliable results, which is essential for advancing the field. In summary, the utilization of virtual biophilic exposure holds promise in appraising designs prior to construction and assessing their relaxing effects, given the incorporation of appropriate methods of sustainable development. This literature review may serve as a valuable resource for various stakeholders, including designers, built environment professionals, and researchers.

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