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Investigating the role of biophilic design to enhance comfort in residential spaces: human physiological response in immersive virtual environment

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Indoor environments significantly impact human health. The COVID-19 pandemic highlighted the urgency of reconnecting with nature to maintain both physiological and psychological health. Modern indoor lifestyles have increased isolation from nature, diminishing these benefits. While previous studies have demonstrated the positive effects of biophilic design on human physiological comfort, its application in residential spaces remains underexplored. This study investigates how biophilic design elements—including natural light, ventilation, and greenery—influence physiological stress and comfort in residential settings using immersive virtual environments (IVE). Ninety-four participants were exposed to two test environments: one with biophilic elements and one without. Measurements of skin conductance level (SCL) and blood pressure (BP) were recorded across three phases: relaxation, exposure to mild stressors, and recovery. The results revealed a significant reduction in SCL in biophilic environments ($\Delta M = -0.38$) compared to non-biophilic environments ($\Delta M = -0.19$). However, BP levels remained unaffected across both experiments. These findings suggest that biophilic design positively influences stress recovery and comfort, underscoring its potential in residential applications.

KEYWORDS

biophilic design, human physiological comfort, residential spaces, virtual reality, blood pressure (BP), skin conductance level (SCL)

1 Introduction

Recently, the environmental impact on humans has become a significant area of research following the COVID-19 pandemic, which altered habits, lifestyles, and increased interest in nature, directly influencing human health (Maharani and Fitriyanto, 2022). Historically, humans have been connected to nature in various ways; however, modernized life and technological advancements have increasingly distanced humans from nature. As people now spend most of their time indoors (Klepeis et al., 2001), opportunities to experience nature have diminished. The COVID-19 pandemic has demonstrated the urgent need to reconnect humans with nature to support mental health and comfort, one approach being the incorporation of biophilic design into interior spaces. Integrating biophilic elements into built environments can create more comfortable spaces, encouraging individuals to spend more time and maintain frequent connections with natural elements while indoors (Karaman and Selçuk, 2022). While biophilic design's impact on psychological responses has been well-documented (Gillis and Gatersleben, 2015), there is limited research on its effects on physiological responses during stress recovery (Li and Sullivan, 2016). Furthermore, little is known about how specific elements of biophilic design, such as greenery, views of nature, and bioforms, contribute to comfort (Yin et al., 2019).

1.1 Research problem

The COVID-19 pandemic has restricted everyone's movement; work, school, and other activities have shifted entirely to the home environment (Maharani and Fitriyanto, 2022). Limited space and inadequate rooms in residential settings present unique challenges in making these spaces comfortable. Exploring new methods to optimize interior environments is essential to enhance resident comfort. The biophilic design principle has been shown in various studies to positively influence people's physiological health by reducing stress and increasing comfort (Zhang et al., 2022). Human health benefits significantly from nature's influence, including exposure to sunlight and fresh air, which are fundamental components of biophilic design principles.

1.2 Research aims and objective

The research aims to highlight the urgent need to reconnect humans with nature by employing biophilic design principles, particularly focusing on "direct contact with natural features," due to its critical role in enhancing comfort in residential spaces.

The objective is to investigate physiological responses as indicators of stress and comfort by examining the effects of implementing biophilic design in a full-scale room using immersive virtual environments (IVE).

2 Literature review

2.1 Biophilic design

The world is urbanizing at an unprecedented rate (Turner et al., 2004), and city life is often associated with long working hours (Facey et al., 2015). People now spend most of their time indoors (Klepeis et al., 2001), (Yin et al., 2019), which further disconnects them from nature (Yin et al., 2020), leading to increased stress-related illnesses (Van Os et al., 2010), higher mortality rates, and chronic illnesses (World Health Organization, 2021). This trend is largely attributed to the lack of natural elements in built environments (Yin et al., 2018). Research conducted over several decades has consistently shown that connecting with nature has positive effects on human health and wellbeing (Frumkin, 2001). Experimental studies confirm that exposure to nature reduces stress (Berman et al., 2012), improves productivity (Lohr et al., 1996), boosts immune function, and enhances the sympathetic nervous system (Berto, 2014). Biophilic design fosters deeper engagement with nature (Huizi et al., 2024), incorporating sensory elements like sound, texture, smell, and visual cues, either directly or indirectly (Nitu et al., 2022). By integrating biophilic elements into built environments, such as greenery and natural light, it is possible to create more comfortable spaces that reflect natural life (Karaman and Selçuk, 2022). Furthermore, studies have explored the interplay between humans and their environment, considering aspects like greenery (Johnstone et al., 2022; Kimic and Kundziewicz, 2020; Talebpour et al., 2020), restorative theory (Lehmann, 2021), biodiversity (Harvey et al., 2020), and ecological perspectives (Nieuwenhuijsen et al., 2021).

Although biophilic design has extensively summarized its psychological benefits (Gillis and Gatersleben, 2015), studies exploring its impact on physiological responses during stress recovery remain limited (Li and Sullivan, 2016). Furthermore, little is known about how individual elements of biophilic design, such as greenery, distant views of nature, or bioforms, contribute to comfort (Yin et al., 2019). In recent years, researchers like Bolten and Barbiero (2023), Downton et al. (2017), Zhong et al. (2022), and Zebua and Putra (2022) have emphasized biophilic design's application in various buildings, including workplaces, libraries, hospitals, mosques, and shopping centers. This growing body of research demonstrates the significant benefits of biophilic design (Abraham et al., 2023). For instance, studies conducted by Huizi et al. (2024) highlight the positive influence of biophilic environments in schools, particularly regarding children's wellbeing and health. Their research on biophilic integration in Chinese kindergarten environments underscores its potential to enhance children's health and overall development.

2.1.1 Biophilia: hypothesis and theory

The term "biophilia" was defined in ancient Greece as "love of life" (Baratto, 2024) or "living system" and was later introduced by psychoanalyst Erich Fromm in 1964 (Newman, 1964). Recently, biophilia has been recognized within international building evaluation systems as a fundamental category of architectural design (Jiang et al., 2020), gaining increasing attention in the global architecture industry (Ünal and Özen, 2021). Today, various building standards and green building rating frameworks incorporate "biophilic design" into their evaluation criteria (Zhong et al., 2024). For instance, the WELL Building Standard v2 (launched in 2020) emphasizes the 'Provide Association to Nature' concept within the "Mind" category, promoting biophilic design in both indoor and outdoor spaces to enhance mental and physiological wellbeing (Well Building Standard, 2024). Similarly, the Living Building Challenge (LBC) 4.1 (updated in 2024) explicitly identifies biophilic design ("Beauty + Biophilia") as a key goal, requiring projects to integrate nature into building designs and operations (International Living Future Institute, 2024). Additionally, the LEED v5 (released in 2024) includes "Connecting with Nature" as a credit, encouraging project teams to develop and implement comprehensive biophilic design strategies (LEED, 2024).

The biophilia hypothesis is supported by two complementary theories: Attention Restoration Theory (ART) and Stress

Recovery Theory (SRT). ART posits that natural environments with “gentle enchantment” can replenish human cognitive abilities, reducing mental fatigue and improving concentration (Kaplan, 1995). Meanwhile, SRT suggests that exposure to nature activates the parasympathetic nervous system, aiding stress recovery as our innate preference for natural environments evolved over time (Ulrich et al., 1991). While the specific mechanisms through which nature affects human health remain debated, both theories demonstrate that exposure to natural environments can enhance resilience by promoting attentional recovery and reducing psychophysiological stress (Markevych et al., 2017). This hypothesis underpins biophilic design, which integrates natural features and systems into indoor environments (Mehaffy, 2012).

2.1.2 Pattern of biophilic design to enhance human comfort and stress

Biophilic design refers to the incorporation of natural elements into architecture, such as natural materials, window views of nature, curved edges, and greenery (Ryan and Browning, 2020). It can be categorized into three types of experiences: direct experience of nature, indirect experience of nature, and the experience of space and place. The 24 attributes of biophilic design provide a framework to understand and thoughtfully integrate diverse strategies into the built environment (Kellert and Calabrese, 2015). This research emphasizes the inclusion of natural light, natural ventilation, and plants, as these elements have been proven in previous studies to reduce stress and positively impact comfort (Mehaffy, 2012), (Kim and Kim, 2007). These elements were chosen due to their significant benefits and low cost of implementation.

2.1.2.1 Natural light

Natural light is an important factor in residential environments. It possesses a desirable quality and has a significant impact on both conscious and unconscious memory. Incorporating natural light into indoor spaces offers numerous benefits for the human body, making it easier and more comfortable to perform various tasks (Kim and Kim, 2007), while also actively regulating circadian rhythms, mood, and behavior (Eissa et al., 2022). Fortunately, creative biophilic design can greatly enhance the penetration of natural light into building interiors. Design strategies that introduce natural light into interior spaces often include glass walls, clerestory windows, skylights, atria, reflective colors and materials, and path-following mirrors that reflect sunlight into the interior space (Kellert, 2018).

2.1.2.2 Natural ventilation

“Natural ventilation” refers to the airflow into or out of a building through openings designed within the building envelope, driven by pressure naturally created by the wind (Awbi, 2002). It is important for human comfort and productivity. The experience of natural ventilation in built environments can be enhanced by changes in air flow, temperature, humidity, and barometric pressure. These conditions can be achieved through external access by simple means, such as operable windows, or through more complex engineering and technological strategies (Nieuwenhuijsen et al., 2021). Biophilic design strategies aim to enhance natural ventilation by maximizing airflow through the strategic placement of operable windows and vents, reducing dependence on HVAC systems, and maintaining a comfortable temperature and air movement. These strategies include operable windows, vents, narrower rooms and structures, and stacking effects. The simplest way to improve natural ventilation is by increasing outdoor access through balconies, porches, decks, large operable windows, and similar structures (Kellert, 2018).

2.1.2.3 Plant

Plants are among the rare living organisms that can easily integrate into buildings (Kellert, 2018). Vegetation, such as flowering plants, is one of the most effective ways to bring the direct experience of nature into indoor spaces (Kellert and Calabrese, 2015). It improves humidity levels by releasing moisture into the air through transpiration, which prevents dryness and enhances air quality. Plants are often incorporated into the landscape around buildings, in building interiors, and in transition spaces that mark pathways between indoor and outdoor environments (Kellert, 2018). Bringing green plants into indoor spaces can help reduce stress. Studies show that small, lightly scented green plants are optimal for health, wellbeing, and a sense of comfort (Beukeboom et al., 2012). Significant advances in knowledge and technology have facilitated the adoption of more ambitious and environmentally innovative approaches to integrating greenery into buildings. For example, these approaches include vertical green walls or large park-like atriums that help absorb sound, reducing echoes and improving acoustic comfort in busy indoor spaces (Kellert, 2018). Studies by Sharam et al. (2023) have indicated that biophilic interior designs, along with window views of trees and blue skies, enhance creative fluency and overall comfort.

2.2 Comfort psychology

Comfort has been considered one of the key elements in designing architectural spaces since ancient times. Over the past 50 years, it has become an influential and important factor (Rupp et al., 2015). The term “comfortable” refers to a feeling of satisfaction, coziness, or a state of physical wellbeing (Bardwick, 1995). On the other hand, “uncomfortable” describes stress or negative emotions that interfere with psychological recovery (Thompson et al., 2022; Noelke et al., 2016). Numerous studies have shown that comfort depends on several factors that interact with psychological recovery (Jin et al., 2020; Yan et al., 2023) and affect one or more indoor environmental factors, such as indoor thermal conditions (Lafortezza et al., 2009), indoor air quality (IAQ) (Andargie et al., 2019), indoor visual conditions (Yuko et al., 2007), and indoor acoustic conditions (Herranz-Pascual et al., 2019).

Enhancing visual comfort in residential buildings focuses on creating living spaces that promote happiness, productivity, and satisfaction through optimized design and lighting (Karimi et al., 2023; Peters and Halleran, 2021). This can be achieved by incorporating large windows and using architectural features such as bay windows, clerestory windows, large picture windows, or skylights to maximize natural light. These features reduce the need for artificial lighting and connect residents to outdoor spaces (Jegede and Taki, 2021). Additionally, designing spaces to provide pleasant views, such as gardens, greenery, or other aesthetic features, contributes to a sense of peace and wellbeing (Lau and Yang, 2009). The study by Ko et al. (2020) examined the emotional, thermal perception, and cognitive impacts of having an external view through a window in a working environment, as well as the effects on occupant motions and cognitive performance. The findings revealed that individuals near a window may be more tolerant of minor thermal comfort deviations. Having a window in the space enhances mental wellbeing by promoting positive emotions, reducing negative feelings, and providing a visual connection to the outside. This visual connection supports working memory and concentration, which are directly linked to worker productivity.

Improving thermal comfort in apartment design is essential to create a comfortable space, regardless of weather conditions (Mirrahimi et al., 2016). This can be achieved through natural ventilation (Raja et al., 2001), passive solar design principles with south-facing windows, and thick insulation to maximize natural heat gain during the winter months (Berthou et al., 2015). Emphasizing insulation to minimize heat loss, using insulating devices and shades to block direct sunlight, and reducing the cooling load while retaining sufficient natural light (Kim et al., 2013), as well as considering the building's orientation (Haase and Amato, 2009) are other ways to improve thermal comfort.

Enhancing indoor air quality (IAQ) comfort in residential space design is critical to the health and wellbeing of residents (Peters and Halleran, 2021). This can be achieved by designing spaces with operable windows and cross-ventilation to allow fresh outdoor air to circulate (Ahmed et al., 2021), incorporating balconies or outdoor spaces to give residents access to fresh air and outdoor environments, using natural ventilation, and fostering a connection with nature (Peters and Halleran, 2021). Indoor plants, which act as natural air purifiers by removing pollutants and increasing oxygen levels, can also be integrated (Deng and Deng, 2018). Increasing ceiling height is another common factor that impacts the quality of the indoor experience (Meyers-Levy and Zhu, 2007).

The relationship between comfort conditions and the incorporation of biophilic design elements in spaces is symbiotic (Wolfs, 2015). As shown in Figure 1, using these elements can enhance the wellbeing of occupants (Kellert, 2018). Biophilic design, which stems from our connection to nature, aims to integrate natural elements and experiences into the built environment. When applied to architecture, it creates spaces that prioritize both physical and psychological comfort (Downton et al., 2017). Architectural features, such as windows that frame views of the outdoors and the inclusion of indoor plants, not only bring nature indoors but also contribute to improved thermal comfort and air quality (Peters and D'Penna, 2020). The visual connection with greenery and abundant natural light reduces stress levels, enhances wellbeing, and improves mental comfort (Altomonte, 2008).

Furthermore, biophilic design promotes adaptable spaces that allow residents to customize their environments according to their preferences for optimal comfort. For instance, adjustable shading systems provide the ability to manage light and maintain comfort (Nitu et al., 2022).

2.3 The use of virtual reality in psychology

Psychology is a broad field that involves understanding the mind and how it influences human behavior (Hakim and Hammad, 2021). It has further evolved with the adoption of immersive technologies

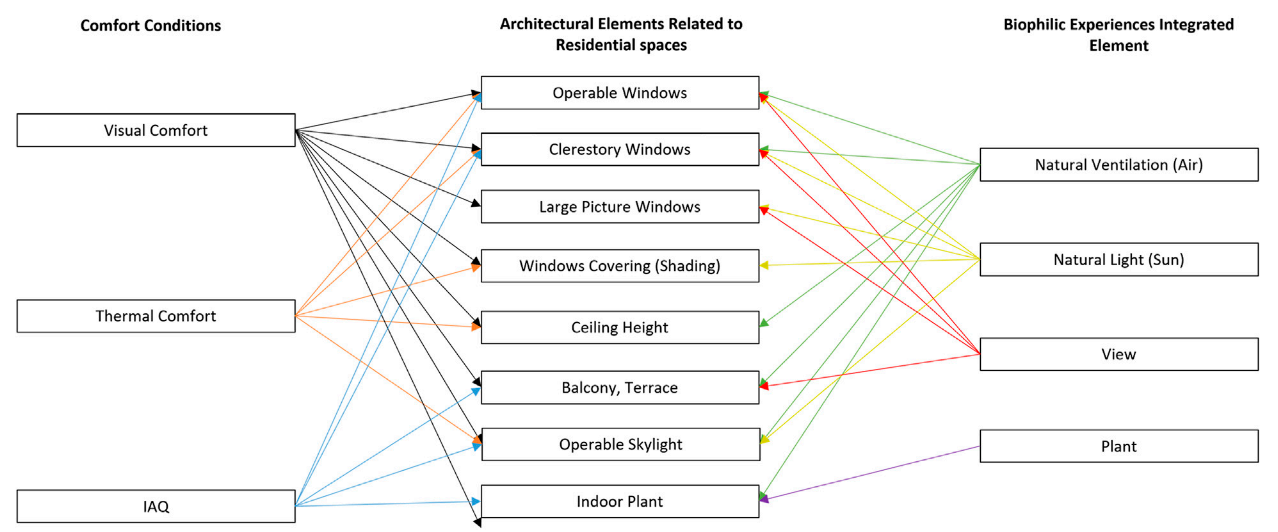


FIGURE 1
Relationship between comfort conditions and biophilic design elements and applied them in residential spaces through different architectural elements (Source: authors).

and virtual environments (VE). Virtual reality (VR), a subfield of immersive technology, is widely used in psychology. VR is defined as a technology that "...(generates) a graphical environment that makes both users feel like they are physically present in a virtual world and also allows them to interact in real time" (Botella Arbona et al., 2014). Using sensory input from specially designed head and hand devices, VR headsets are equipped with viewing optics for each eye, providing a 360-degree viewing experience (Hakim and Hammad, 2021). The use of virtual reality in psychology not only enhances human interaction but also enables researchers to conduct studies that would be impossible in the real world. Assessing an individual's experience, cognition, and behavior through paper-and-pencil testing is very challenging. The advantage of using virtual environments (VE) in psychology lies in the fact that movements in virtual space and the accompanying changes in perception are processed by the brain in the same way as movements in real space (Foreman, 2009).

3 Methodology

After reviewing the relevant literature, the researchers identified a knowledge gap regarding the effect of biophilic environments on the physiological state of occupants in residential spaces. Specifically, they sought to understand how the incorporation of biophilic design into internal spaces affects the occupants' physiological response to comfort. The researchers employed an empirical approach by developing a controlled experiment to study the effect of biophilic design on the physiological responses of subjects in an internal environment using immersive virtual reality (IVR). The research utilized a between-subjects design to investigate these responses. The physiological responses studied were blood pressure and skin conductance. The study comprised three phases: a baseline phase, a stress phase, and a recovery phase, aimed at comparing stress reduction through VR. During all three phases, the physiological readings of participants were recorded. The first phase established a baseline for all participants. The second phase focused on the participants' physiological response to a mild stressor in the test environment. In the final phase, participants were allowed to relax in the test environment to provide feedback and data on their physiological recovery process.

Additionally, the researcher collected participants' demographic information and feedback about their perceived experiences in these environments. Finally, all data collected in this experiment were processed and analyzed empirically using the SPSS statistical program to test the hypothesis: "Using biophilic principles in residential spaces will positively contribute to mental health and provide a sense of comfort," in order to either support or refute the hypothesis. The following charts summarize the methodological framework approaches, as shown in Figure 2.

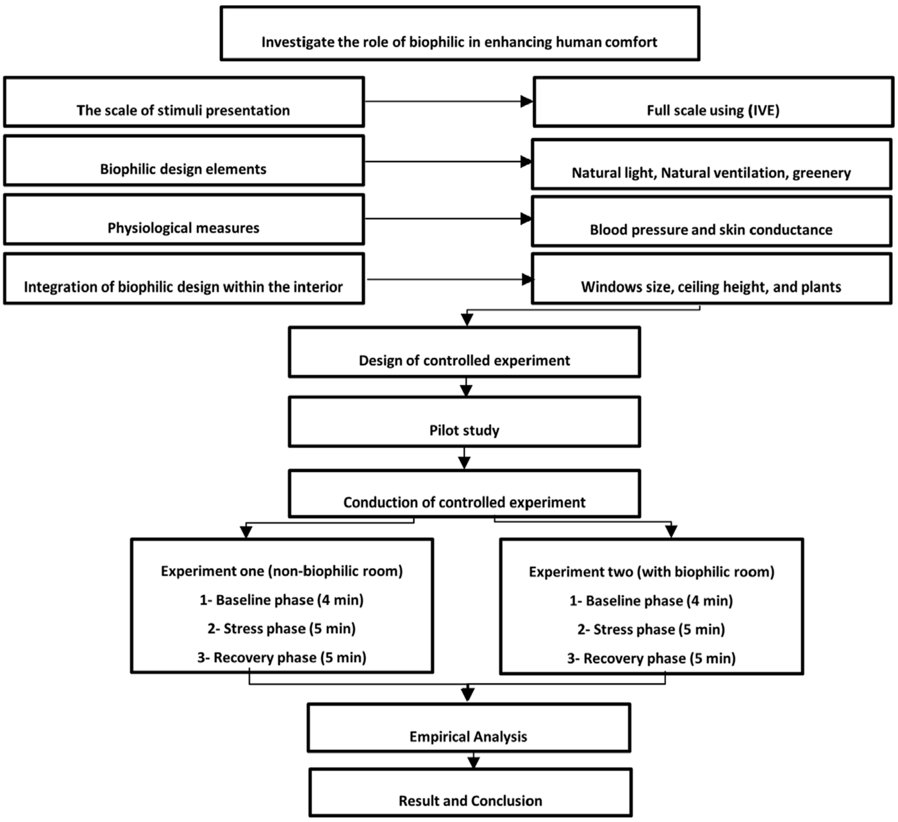


FIGURE 2
Methodological framework approaches (Source: The Authors, 2023).

3.1 Experiment design

This experiment focused on examining the visual influence of biophilic elements on human comfort and stress psychology within interior environments. The researchers assessed participants' responses in a single interior space with various biophilic elements by stimulating two 3D virtual rooms in VR, using SketchUp 2022 with Enscape (version 3.4). Two distinct environments were designed: one containing non-biophilic elements and the other incorporating biophilic elements (e.g., natural light, natural ventilation, and green areas). The biophilic space featured a large window, a clerestory window, a ceiling height of about 4 m with natural light from the window, and indoor and outdoor plants, as shown in Figure 3. Each participant visited the two environments on separate days. During each visit, they encountered only one environment, with the rationale for conducting one experiment per day being to allow physiological changes to return to normal.

3.2 Participation

The experiment was conducted with 94 participants (55 female and 39 male), aged between 18 and 45 years. None of the participants had chronic diseases such as high blood pressure, heart disease, or diabetes, and they were not taking any medications for stress or anxiety. The experiment was conducted over a specific period between August 2023 and November 2023. All participants gave their informed consent for inclusion before they participated in the study, and their participation was voluntary without compensation.

3.3 Outcome measures

Blood pressure (BP), heart rate (HR) (Tang et al., 2022), heart rate variability (HRV) (Morresi et al., 2021), and skin conductance level (SCL) (Gerrett et al., 2013) were measured using a wearable biomonitoring sensor as physiological indicators of the acute stress response (Yin et al., 2019). In this study, skin conductance and blood pressure are used as indicators of physiological stress.

3.3.1 Skin conductance level

The skin conductance of participants in this study was recorded using the eSense skin response sensor (Mindfield Biosystems, Inc., Berlin, Germany) with the eSense app on an iPad, as used in the previous study (Grasser et al., 2022). The term "skin conductivity" refers to measurable changes in the bioelectric properties of the skin. Skin conductivity depends on the activity of the skin's sweat glands and responds to even the smallest changes that we may not perceive, such as wet hands. A very small voltage, which is completely harmless and imperceptible, is applied to the skin through the two electrodes of the eSense Skin Response, across which a small electric current flows. Increased activity of the sweat glands results in more skin moisture, which enhances the conductivity of the electrical current. As a result, skin conductivity increases.

3.3.2 Blood pressure

Recording the blood pressure of participants in this study was done using an automatic upper-arm blood pressure monitor, the "Max Blood Pressure Monitor." This monitor consists of a cuff (with the so-called "air chamber") connected to an electronic control panel. The device performs functions such as cuff inflation and deflation, data collection (through special sensors), data processing, and display.

3.4 Stress inducers

Different methods have been used to induce stress in controlled experimental environments by various researchers (Yin et al., 2018; Fich et al., 2014). One such method is the Trier Social Stress Test (TSST) (Kirschbaum et al., 1993), a standardized procedure designed to elicit a mild stress response by asking participants to prepare and present a speech to a panel of judges, in addition to performing a verbal arithmetic task. Due to the time-consuming nature of the full TSST, it could not be utilized in this study. Therefore, a modified version of the test was adapted for use in the Immersive Virtual Environment (IVE) to elevate participants' perception of these stressors within a shorter time frame.

Participants were required to complete a verbal arithmetic task within a time limit. This task, aimed at inducing stress related to mental performance, involved participants subtracting 13 from a 4-digit starting number displayed on a virtual screen, and verbally reporting the intermediate result. Each number was shown for only two and a half seconds. When participants made a mistake, they were instructed to restart from the same initial number. Additionally, a countdown of the

FIGURE 3
Two environmental simulations in VR: **(A)** Room with non-biophilic elements, **(B)** Room with biophilic elements (Source: authors).

FIGURE 4
Experimental condition for participants during the experimental, the participants were wearing VR head-mounted displays and biomonitoring sensors, consents form obtained by the individual (Source: authors).

remaining time was displayed on the screen, further increasing performance-related stress.

3.5 Experimental procedure

The experiment consisted of three parts: preparation and baseline, stress, and recovery. First, the researcher explained the experimental procedure and asked participants to sign the consent form for 3 min. Then the researchers configured the VR head-mounted display and biomonitoring sensors. The blood pressure monitor was connected to the left arm, while the two electrodes of the eSense skin response sensor were connected to the index and ring fingers of the participant's right hand, as shown in Figure 4.

In each environment, participants began by resting for 4 min in a seated position, with only the grey picture displayed in VR. Participants were instructed to limit body movements to a minimum, as any movement could affect the sensor's measurements, and to freely observe the environment during this time. Additionally, unless otherwise instructed, they were to remain silent and only speak if they experienced nausea or discomfort that prevented them from continuing the test. This phase allowed their physiological conditions to stabilize (Yin et al., 2019). Blood pressure (BP) baseline data was collected at the end of this period, and skin conductance level (SCL) data was collected from the beginning of this phase.

After the baseline phase, during the stressor period, participants were exposed to a 2D screen and instructed to complete a stress-inducing arithmetic task for 5 min. Upon completing the task, pre-recovery BP data was collected. In the final phase (recovery phase), participants were randomly assigned to be virtually exposed to the internal environment of the room for 5 min. Previous research has indicated that this duration is sufficient to alter acute physiological stress levels (Yin et al., 2018). Post-recovery BP data was collected at the end of the third phase. SCL data was recorded throughout all three phases of the experiment.

At the conclusion of the study, all devices, sensors, and monitors were removed from the participants, who then completed a 5-min

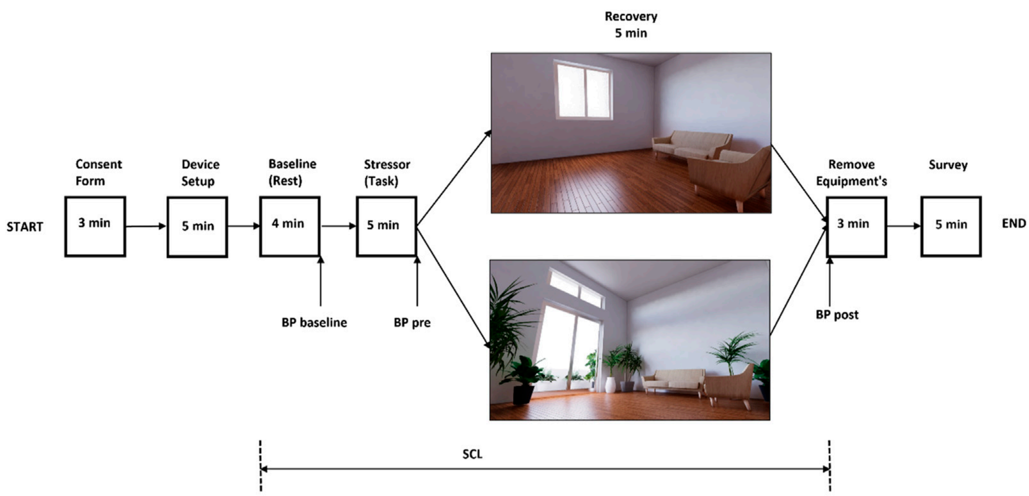


FIGURE 5
Experimental procedure (BP, Blood pressure; SCL, Skin conductance level); Source: authors.

paper survey. The full experiment took 30 min per session, as illustrated in Figure 5.

4 Result and analysis

All the data were collected and analyzed using SPSS version 26. First, the authors presented the participants of the experiment and their demographic data. Next, skin conductance data and blood pressure data were independently presented and analyzed according to the three phases of the experiment. All analytical procedures used were non-parametric. Friedman tests (Belyusar et al., 2015) were applied to compare differences in responses within groups across the different experimental phases, while Mann-Whitney tests were used to compare results between groups.

4.1 Participants

A total of 94 people voluntarily participated in this experiment. None of the participants had prior experience with VR or head-mounted displays. Most participants reported being in very good or excellent health and having had a good night's sleep before the experiment. They were required not to take any medications for stress or anxiety. All participants confirmed that they did not feel nervous on the day of the experiment and reported feeling comfortable in the biophilic room. Each participant took part in both experiments, which were conducted on different days to avoid affecting blood pressure measurements and skin conductivity.

4.2 Skin conductance level data and analysis

4.2.1 Comparison between the three phases of SCL

To ensure differences in SCL values during the three stages, a Friedman test (non-parametric test) was conducted among participants across the three phases. The results indicated a significant difference between the three phases ($p < 0.05$), as shown in Table 1. Subsequently, a comparison between the phases was carried out to validate the Friedman test results, which rejected the null hypothesis that the three phases were similar in the level of skin conductivity among participants. Figure 6 illustrates the pairwise comparison between the average ranks for the three phases. The average rank during the first phase was 1.89, which increased to 2.52 during the second phase and then significantly decreased to 1.50, falling below the first phase. When subtracting the third stage from the second, the standard deviation was higher compared to subtracting the third stage from the first stage. This indicates that during the second stage, the level of skin conductance was significantly higher.

4.2.2 Effects of the experimental setting on SCL

The SCL data was collected for each participant in each group, and the average SCL was calculated for each minute, each phase, and for the biophilic and non-biophilic parts of the experiment, as shown in Table 2. A significant decrease was observed during the first phase, with the arithmetic mean at the beginning of the phase being (M = 2.460 and dropping to (M = 2.10) by the fourth minute for both groups. The SCL then increased during the second phase, reaching (M = 2.30) in the fifth minute and (M = 2.40) in the ninth minute. In the final phase, the SCL values decreased again, with the arithmetic mean in the last minute dropping to (M = 2.22), which was lower than the value recorded at the beginning of the experiment during the first phase (M = 1.97).

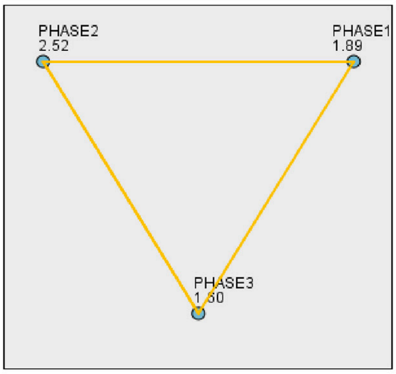
From these preliminary findings, the expected results based on the experiment's design suggest that the first phase allowed participants to relax, while the second phase induced higher stress levels.

Analyzing the first phase minute by minute, the experiment aimed to assess the adequacy of the control setting in establishing controlled initial conditions among participants and enabling them to achieve a calm and unaroused physiological state before transitioning to the subsequent phases. The results indicate a significant and consistent decrease in SCL during this phase, with

TABLE 1 Friedman test for SCL results in the SPSS program.

Hypothesis test summary				
	Null hypothesis	Test	Sig	Decision
1	The distributions of Phase 1, Phase 2, and Phase 3 are the same	Related-samples Friedman's two-way analysis of variance by ranks	0.0	Reject the null hypothesis
Asymptotic significances are displayed. The significance level is 0.05				

Pairwise Comparisons



Each node shows the sample average rank.

Sample1-Sample2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj.Sig.
PHASE3-PHASE1	.289	.103	2.792	.005	.016
PHASE3-PHASE2	.922	.103	8.920	.000	.000
PHASE1-PHASE2	.634-	.103	6.127-	.000	.000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .05.

FIGURE 6
Pairwise comparison between the average rank for the three phases of the two groups; biophilic and non-biophilic.

TABLE 2 Mean of SCL data by group, minutes, and phase.

Phase	Min	Non-biophilic	Biophilic	All samples
		Mean	Mean	Mean
1	0	2.63	2.28	2.46
	1	2.40	2.20	2.30
	2	2.42	2.10	2.26
	3	2.31	2.00	2.15
	4	2.27	1.93	2.10
0–4 min		2.40	2.10	2.25
2	5	2.49	2.10	2.30
	6	2.55	2.18	2.36
	7	2.57	2.26	2.42
	8	2.52	2.30	2.41
	9	2.46	2.34	2.40
5–9 min		2.52	2.24	2.38
3	10	2.36	2.08	2.22
	11	2.33	1.95	2.14
	12	2.34	1.85	2.09
	13	2.32	1.77	2.04
	14	2.31	1.62	1.97
10–14 min		2.33	1.86	2.09

values dropping steadily every two consecutive minutes, from a mean of 2.46 in the first minute to 2.10 in the last minute. This notable trend suggests that participants' skin conductance may settle further if they are allowed more time in the control environment, as SCL also showed a significant decline towards the end of the phase.

In the second phase of the experiment, SCL was analyzed minute by minute for all participants. A test was conducted to evaluate whether the stressors applied during this phase successfully elevated the participants' SCL levels compared to the first phase. The difference in the average SCL values between the two phases was apparent. While there was a slight decline in SCL during the last 2 min of the second phase, this decrease was not statistically significant. These findings demonstrate the adequacy of the stressors used in increasing participants' physiological stress levels.

4.2.3 Group differences in SCL responses

To examine the effects of biophilic and non-biophilic elements on participants' stress recovery, the Mann-Whitney test revealed statistically significant differences between the two groups during the third phase of the experiment at a significance level of ($p = 0.05$). The median SCL value for the biophilic group (−0.31) was lower than that of the non-biophilic group (−0.12), indicating that stress levels were lower for the biophilic group.

4.3 Blood pressure data and analysis

After analyzing the skin conductance level (SCL) data, the systolic blood pressure (BP) results were examined using the Friedman test. The analysis revealed no significant differences between the three stages (BP base, BP pre, and BP post) concerning the BP variable. This indicates that position did not contribute to a statistically significant increase in blood pressure at a significance level of $p < 0.05$, as shown in Table 3.

5 Discussion

This study examined the physiological responses to biophilic elements in an indoor environment. The results indicate that incorporating biophilic elements into indoor space design has positive effects, as evidenced by changes in skin conductance levels.

The physiological findings consistently demonstrated that biophilic interventions, such as the inclusion of internal and external plants and daylight, had a beneficial effect in reducing stress levels compared to non-biophilic environments. Figure 7 highlights a decrease in the mean and median SCL values for participants during the third phase in a room with biophilic elements, compared to a smaller decrease in a room without such elements. These positive effects of biophilic interventions on SCL align with previous studies on the health benefits of windows, daylight, and indoor green plants (Yin et al., 2020).

The findings regarding physiological responses during the recovery process align with previous studies inspired by the Stress Recovery Theory (SRT), which proposes that humans have an innate preference for natural environments. SRT suggests that viewing natural environments can reduce physiological stress and aversion (Ulrich et al., 1991; Park et al., 2010; Largo-Wight et al., 2011). According to SRT, natural elements, such as sights and sounds, activate the parasympathetic nervous system, resulting in lower heart rate, blood pressure, skin conductance, and salivary cortisol levels. These physiological responses promote relaxation and help reduce stress and autonomic arousal. This mechanism is rooted in human evolution and our innate connection to the natural world (Ulrich et al., 1991).

TABLE 3 Friedman test for SCL results in the SPSS program.

Hypothesis test summary				
	Null hypothesis	Test	Sig	Decision
1	The distributions of BP base BP pre, and BP post are the same	Related-samples Friedman's two-way analysis of variance by ranks	0.104	Retain the null hypothesis
Asymptotic significances are displayed. The significance level is 0.05				

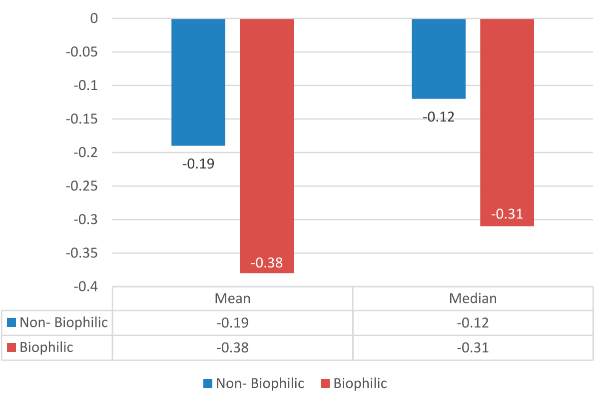


FIGURE 7
Comparing the mean and median of SCL values for participants in the two experimental.

These findings support the feasibility of incorporating biophilic design into indoor environments as a strategy to positively impact human health and enhance comfort. Through this research, key steps for implementing biophilic design elements in residential spaces were summarized as follows:

1. Research and Analysis Stage: Understanding the local climate, surrounding environment, and cultural context is essential. This involves analyzing the site by considering factors such as sun movement, wind direction, and existing vegetation.
2. Site Evaluation: Conduct a comprehensive site study to identify opportunities for incorporating biophilic features. Evaluate outdoor spaces, natural light availability, existing plants, and scenic views.
3. Planning Windows and Openings: Strategically plan the placement and types of windows and openings to maximize views of nature, allow natural light to permeate the space, and enhance airflow. Table 4 outlines proposed design criteria.
4. Incorporating Indoor Plants: Select suitable plants for the indoor environment and place them strategically to enhance visual appeal, improve air quality, and provide diversity through features like plant beds or green walls, as shown in Table 5.
5. Using Higher Ceilings: Incorporate higher ceilings to improve cross-ventilation by increasing the volume of air movement and reducing airflow obstruction. Table 6 provides some proposed design criteria.
6. Implementation and Maintenance: Opt for biophilic design elements that are cost-effective in terms of maintenance and ensure their longevity over time.

TABLE 4 Proposed design criteria using biophilic elements for opening windows.

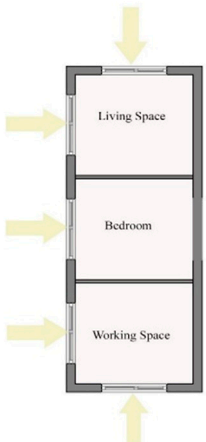
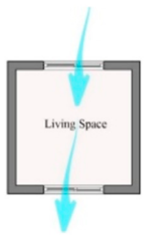
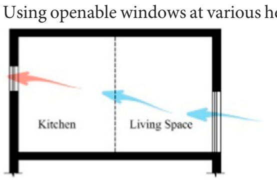
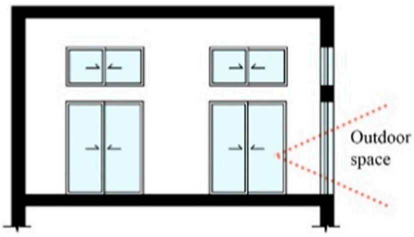
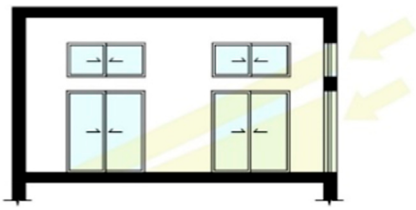
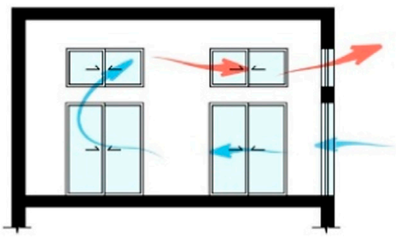
Opening windows	Proposed design criteria
1. It has been shown that incorporating natural light into living spaces can reduce stress and increase comfort. Previous studies have demonstrated that physiological tests indicate the presence of sunlight has an objective effect on reducing sleepiness (Sanchez et al., 2018). Daylight is also essential for referencing biophilic design patterns and for adhering to COVID-19 health protocols (Maharani and Fitriyanto, 2022)	Using large windows and bringing light into the room from two sides in living and working spaces, while attempting to bring light from one side in the sleeping space 
2. Natural ventilation through window openings is preferable to mechanical ventilation (Stavrakakis et al., 2012), as it allows for air exchange and sunlight to enter the home. Biophilic design patterns also necessitate natural ventilation	The cross-ventilation method is used to facilitate air movement within the room 
3. Openable windows in living and cooking spaces are crucial for maintaining good indoor air quality and thermal comfort. This enhances the comfort and health of apartment residents (Peters and Halleran, 2021)	Using openable windows at various heights can further improve air quality within the space 

TABLE 5 Proposed design criteria using biophilic elements for greenery.

Greenery	Proposed design criteria
1. The presence of green spaces reduces stress levels and increases alertness in the afternoon (biophilic design pattern). As previously mentioned, openings are essential for access to green spaces and fresh air (Sanchez et al., 2018)	Integrating natural elements, such as indoor plants and living walls, enhances the overall living environment 
2. Housing strategies should prioritize more livable spaces with green spaces (biophilic design patterns). Green spaces also help meet fresh air needs as they also contribute to the supply of fresh air to housing units	Balconies and overhangs beside windows can be used to create natural green spaces 

TABLE 6 Proposed design criteria using biophilic elements for ceiling height.

Ceiling height	Proposed design criteria
1. High ceilings feature large windows or doors that provide excellent views of the surrounding environment. Increased visual contact with nature can enhance a sense of wellbeing and tranquility	
2. Ceiling height affects the distribution of natural light within a space. Biophilic designs often incorporate strategies to maximize daylight. Higher ceilings can facilitate the influx of natural light, thereby reducing reliance on artificial lighting and offering a more natural and dynamic lighting environment	Using high windows and clerestory windows helps to further maximize the amount of natural light entering spaces 
3. Ceiling height can play a significant role in natural ventilation within a space. Natural ventilation refers to the process of supplying fresh air to an indoor space without the use of mechanical systems	The use of openable windows at different heights can help improve air quality within the space 

These design stages can be applied to three-dimensional models and presented to residential space owners using immersive virtual reality technology. This allows them to visualize the space and make modifications before the implementation process.

The next step is to integrate the proposed design criteria into easy-to-read guidelines. The previously proposed design criteria were simplified to the following symbols: window opening = W, greenery = G, and ceiling height = H. The guideline for a 3-bedroom unit can be seen in Figure 8.

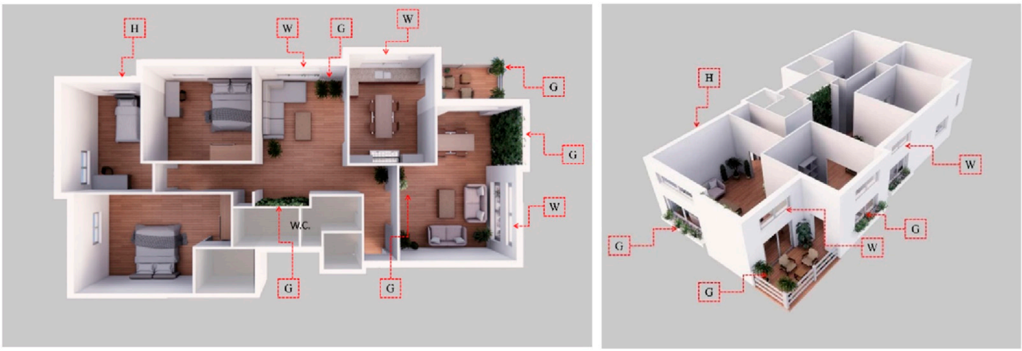


FIGURE 8
3D design guideline for a 3-bedroom unit incorporating biophilic design elements (natural light, natural ventilation, and plants) through using different architectural elements such as: increasing ceiling height and using large and clerestory windows. (Source: authors).

6 Conclusion, limitations, and recommendations for future studies

This paper highlights the importance of integrating biophilic elements within residential spaces, focusing on three key elements: natural lighting, natural ventilation, and green spaces. The rationale for choosing these elements stems from their low cost and the pressing need to reconnect humans with nature, especially in the wake of the COVID-19 pandemic. These elements help create comfortable interior environments for residents.

The paper also reviews the effects of biophilic elements on blood pressure and skin conductance levels through an experiment involving immersive virtual reality technology. The results support the importance of incorporating biophilic elements into residential spaces.

The study confirms that incorporating nature into design reduces stress, enhances wellbeing, and improves overall comfort by engaging our innate connection to the natural world. This is supported by Ulrich et al. (Kaplan, 1995), who found that views of nature significantly reduce stress, as evidenced by faster recovery times and lower cortisol levels in hospital patients with views of greenery compared to those with urban views. Additionally, a study by González-Lezcano (González-Lezcano, 2023) emphasizes the integration of biophilic design principles as a critical strategy for creating healthier and more efficient buildings. González-Lezcano stresses the importance of improving indoor environmental quality (IEQ) by maximizing access to daylight, improving views of nature, and incorporating features that promote wellbeing and physiological comfort. These measures are essential for fostering health-focused environments, particularly in response to challenges like indoor air pollution and the need for post-pandemic resilience in building design.

The paper concludes with recommendations for designing residential spaces by integrating architectural elements with biophilic features.

6.1 Limitations

This study has several major limitations that should be addressed in future research when possible:

- The small sample size resulted in lower statistical power and increased the margin of error.
- Individual differences in comfort, as comfort is a subjective experience influenced by personal preferences, cannot be generalized to all people.
- Virtual environments may not accurately replicate real-world environments, as physiological responses in virtual reality may differ from those in real life. Studies have shown that stress recovery is also related to factors such as hearing, smell, thermal comfort, and human interaction with the environment (Gaoua, 2010; Hedblom et al., 2019). The VR simulation in this study does not include elements present in reality.
- Research by Chantranupong and Sabatini (Chantranupong and Sabatini, 2018) showed that filtering sunlight through windows in real-world applications increases hormonal changes (e.g., serotonin), leading to greater improvements in mood and cognitive abilities. However, VR allows researchers to isolate and investigate specific aspects (e.g., visual impact) that real-world studies may not be able to separate due to the complexity of sensory elements (e.g., noise, light, temperature) (Yin et al., 2020).
- The duration of exposure to virtual environments may not reflect the long-term effects of biophilic design in actual residential spaces.
- It is difficult to control a person's psychological state across different days for an experiment, as measurements in the first stage may vary due to fluctuations in psychological state from day to day.
- The study was conducted across different buildings, limiting the ability to analyze natural factors such as air quality and odors, and assess potential interactions with key design elements.
- VR can cause discomfort due to a mismatch between visual input and the body's sense of movement. Users who experience motion sickness or dizziness may not be able to

participate for extended periods, which limits the applicability of VR to real-life scenarios, particularly in activities involving continuous or rapid motion.

- VR requires users to adapt to unfamiliar controls, new interaction patterns, and artificial environments, which can impose cognitive load not present in natural settings. This raises questions about how accurately VR results reflect real-world cognitive processing, problem solving, or learning.
- Users often behave differently in VR environments compared to real-world situations. They may take more risks, engage in unusual activities, or respond differently to stimuli. These behavioral differences make it challenging to generalize VR results to real-life behavior.
- Virtual reality may train individuals to respond to specific scenarios within the virtual world, but their reactions in similar real-world scenarios may differ due to the lack of sensory attunement or emotional detachment often experienced in VR.

6.2 Recommendations for future studies

The current study examines the impact of biophilic design in residential settings. Future research should include more diverse populations across different environmental settings, such as hospitals, classrooms, or other rooms within residential spaces (Yin et al., 2018). Additionally, the use of self-report measures to assess effects may introduce limitations to the internal validity of the study due to social desirability bias (Kantowitz et al., 2014). Therefore, it may be beneficial to incorporate objective physiological measures (e.g., brain imaging, ECG, salivary cortisol, or heart rate) alongside self-reported outcome measures in future research (Vaisvaser et al., 2013).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The theoretical and empirical studies were approved by the School of Graduate Studies, the University of Jordan. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

HA: Conceptualization, Investigation, Methodology, Software, Visualization, Writing–original draft, Writing–review and editing. WA-A: Conceptualization, Methodology, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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