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Forest digital twin as a relaxation environment: A pilot study

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Forest environments have been proven beneficial for physiological well-being, supporting relaxation and meditative processes. Unfortunately, some groups, predominantly those with reduced mobility, are prevented from forest visitation. Presenting such environments in virtual reality could provide a viable substitute. However, as forest structure and composition are important aspects of its restorative power, to accurately compare the efficacy of virtual forests to that of real natural spaces, the virtual environment should match the real location as closely as possible. Furthermore, if participants achieve similar benefits in both settings, virtual copies (digital twins) of forests could be a viable option for studying forest bathing in a controlled environment. We collected LiDAR scans of a forest location near Prague, took spatial audio recordings of the forest ambiance, and built the forest's digital twin in Unreal Engine. To compare the therapeutic efficacy of the virtual forest with its real counterpart, groups of volunteers spent half an hour in either the real forest, the virtual forest, or both. We collected participants' demographic and psychometric data, assessing their relaxation, emotional state, and cybersickness before and after the session. Our data show an increase in relaxation with no significant differences between the environments, although participants' emotional states did not improve in either condition. We found that participants' experiences were comparable between the environments, but cybersickness limited the potential efficacy of virtual forest bathing. The limitations of the virtual forests as a platform for research into forest bathing are discussed.

KEYWORDS

virtual reality, forest bathing (shinrin-yoku), lidar, nature, stress, digital twin, relaxation, well-being

1 Introduction

A rapidly growing body of research shows that spending time in a forest environment, also known as forest bathing or shinrin-yoku (森林浴), benefits health and well-being. Several systematic reviews based on dozens of studies have reported that forest bathing improves psychophysical stress (Antonelli et al., 2022; Kondo et al., 2018) and anxiety and depression (Hansen et al., 2017; Rosa et al., 2021; Kotera et al., 2022). It has also been demonstrated to benefit diverse conditions, such as cardiovascular and metabolic functions (Ideno et al., 2017; Oh et al., 2017) and reduce inflammatory and allergic reactions (Anderson et al., 2017; Oh et al., 2017). There are also positive effects on cognitive skills (Mygind et al., 2019), emotional balance, and mood of the participants (Corazon et al., 2019). Although the reviews often point out that the studies' quality is heterogeneous and only a few provide substantial evidence, there is general agreement on the positive effect of forest bathing on psychophysical well-being.

1.1 Theories behind forest bathing

Despite abundant studies describing the effects of forest bathing, less attention is dedicated to the underlying theories explaining why forests should be so effective in stress reduction, relaxation, and other health benefits. Three main conceptual frameworks might come into play during forest bathing.

The *biophilia* hypothesis states that forests, as complex systems of many organisms, might fulfill human *biophilia*. *Biophilia* is an innate human need to interact with living organisms and focus on life and life-like processes (Kellert and Wilson, 1995; Wilson, 1984). Because we spent most of our evolutionary history in natural environments, we have adapted to life in nature and are tightly linked to the living. The inborn focus on living organisms was further strengthened through culture by natural themes in myths, religions, or shared dreams (Kellert and Wilson, 1995). The biophilic approach thus considers being in a natural environment as an optimal state. When we are deprived of contact with other organisms, we lose a considerable part of what makes us human (Wilson, 1984).

Attention restoration theory (ART) argues that when we focus on a particular activity for a long time or try doing multiple tasks simultaneously, we face mental fatigue (Kaplan and Kaplan, 1995). A mentally fatigued person becomes irritable, tired, makes mistakes, must invest a lot of effort and energy to focus on a monotonous activity (i.e., *directed attention*), and is easily distracted by other stimuli (*involuntary attention*). One way to restore the capacity for directed attention is to seek an environment that does not require any directed attention. According to ART, natural landscapes with vegetation are ideal, providing a range of stimuli triggering our involuntary attention, but in a subtle and not overwhelming manner, for example, tree branches moving in the gentle wind or the play of light passing through leaves.

The third theory is the *Stress Recovery Theory* by Roger Ulrich (Ulrich, 1983; Ulrich et al., 1991). Stress is an evolutionary response to potentially threatening or harmful situations, but it elicits strong negative emotions, so humans must control it to focus on other important activities. According to Ulrich, stress recovery can be achieved by contact with non-threatening natural environments toward which humans already have positive feelings. We have these positive feelings toward forests, as they are a source of food and shelter, resulting in a perfect stress-reducing environment.

1.2 How to conduct a forest bathing session

As there are multiple theories behind forest bathing, there are also many ways it has been employed in practice and research. Some studies only include forest watching, while others reported walking in a forest or, most typically, a combination of both (for a review, see Park et al. (2010)). It has been suggested that doing any type of physical activity (such as walking) while in a natural setting (the so-called green exercising) has a synergic effect and leads to more significant psychological benefits than a simple presence in nature or physical activity in a non-natural setting (Pretty et al., 2003). Some empirical studies confirm these suggestions (Hartig et al., 2003; Pretty et al., 2007), but during short forest baths, watching and walking seem to have the same effects (Park et al., 2010). Moving freely through a forest allows people to explore it more deeply and on different scales, from finding grand vistas to admiring tiny plants in the undergrowth. And the possibility of exploring the environment and revealing what it can offer is crucial for assessing how people feel (Kaplan, 1988; Kaplan and Kaplan, 1995).

Moreover, forest bathing is a multifactorial experience that stimulates all human senses, and all sensory elements contribute to its outcome (Oh et al., 2020). The visual and auditory aspects of the forest primarily reduce psychophysical stress (Anderson et al., 2017; Franco et al., 2017; Antonelli et al., 2022), and the volatile organic compounds released into the air by trees contribute to the anti-inflammatory and antioxidant effects (Cho et al., 2017). Touching foliage and other plant parts induces calming reactions (Koga and Iwasaki, 2013), and eating berries and other natural products of forests may deepen the connection between humans and the natural environment (Antonelli et al., 2022).

The time spent in the forest also varies considerably across studies (from minutes to several days), but exposures as short as 15 min can result in short-term positive effects (Kotera et al., 2022), and total exposure of at least 120 min per week might lead to a permanent effect (Antonelli et al., 2022; White et al., 2019).

1.3 Virtual environments alternative

Although forest bathing seems to offer a plethora of health benefits, and some countries consider the benefits strong and reliable enough to be prescribed as a means of psychological and physiological recovery (Hansen et al., 2017), there are groups of people who are unable to visit on their own. Many people suffer from physical or cognitive disabilities limiting their free mobility

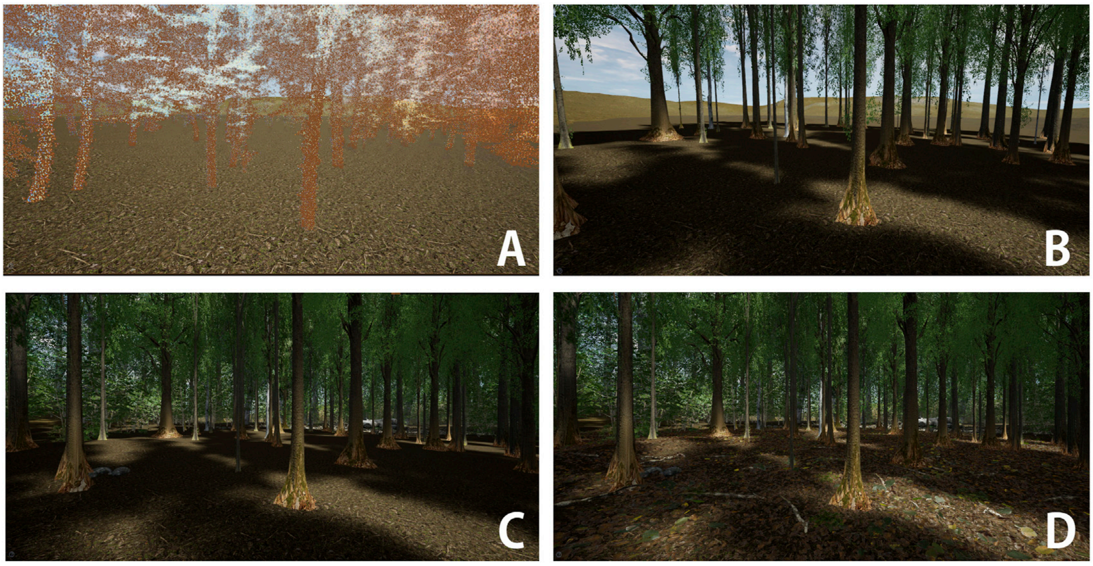

FIGURE 1
Illustration of the virtual forest creation process. Subfigure **(A)** shows the landscape with the visualized lidar point cloud. Subfigure **(B)** shows the placements of trees based on lidar detection algorithms. Subfigure **(C)** shows the environment after surrounding vegetation is added to create a feeling of continuous forest, and subfigure **(D)** displays the final environment with forest floor and undergrowth vegetation.

(D'Cunha et al., 2019), and the elderly population can often feel unfit to travel far or take a walk on uneven ground. Importantly, these groups can often benefit from forest bathing the most (Jia et al., 2016; Mao et al., 2012). Moreover, accessing the forest can be a challenge even for physically fit people. Modern urbanization created places cut away from nature by the city sprawls from which the travel to an uncorrupted natural space can take a few hours (Litleskare et al., 2020; Frost et al., 2022). Also, certain jobs, such as being a submarine worker, arctic scientist, or astronaut, prevent people from experiencing real natural spaces for long periods (Anderson et al., 2017).

Creating virtual environments (VEs) of forest spaces represents an alternative to the real forest bathing, providing a substitute for those unable to visit forests personally (Luo et al., 2022; Reese et al., 2022; Ünal et al., 2022). Current technologies can render accurate visualizations of natural landscapes (see Figure 1) and present them not just as images, 360° videos, or animations but also allow users freedom of movement. Movement in nature has been associated with increased gains. However, most studies investigated only active movement (Barton and Pretty, 2010), not passive movement, such as computer controllers. People can visit these virtual environments on monitors or in projection rooms, and in the last decade, virtual reality (VR) has also become an accessible tool for such research.

VR allows users to visit the virtual environment using a head-mounted device (HMD), which uses stereoscopic projections adding binocular cues to increase the sense of depth, and continuously tracks and translates head movements into natural changes in view. Modern VR HMDs also track body position so users can walk around the virtual environment, improving the feeling of presence and its environment's potential for restorative power. VR has been successfully used in psychotherapy for some time, and the elderly population can significantly benefit from it (Appel et al., 2019).

From the viewpoint of the ART, both virtual and real forests can elicit soft fascination, the sense of being away, providing an escape from habitual activities, and a high degree of compatibility - an agreement between the environment and one's expected activities there. However, the last aspect of the ART—*extent*—might be limited in the virtual forest. *Extent* describes the ability of the environment to encourage exploration and discovery of new features and their integration into more complex patterns. Real forests offer infinite possibilities to discover novel features across multiple scales, from the tiniest detail to landscape levels. The virtual forest, however, lacks some *extent*, primarily when focusing on the simulation visual details or trying to look far away.

VR primarily reflects the forest's visual and auditory components, which is essential for reducing psychophysical stress (Anderson et al., 2017; Franco et al., 2017; Antonelli et al., 2022). The olfactory component could be added to some extent (Abbott and Diaz-Artiles, 2022). However, touch and taste are the senses that cannot be easily simulated in VR yet. Despite the limited sensory stimulation, VR might still have similar effects as the exposure to real forests, as some recently published studies suggest (Björling et al., 2022; Mattila et al., 2020; Reese et al., 2022; Ünal et al., 2022).

1.3.1 Disadvantages of virtual environments

Although VEs can allow more people to benefit from forest restorative power, using them in therapeutic or research settings also brings a few challenges (White et al., 2018; Frost et al., 2022). The major problem VEs create is cybersickness, its primary negative symptoms being nausea, dizziness, eyestrain, and headaches (Kennedy et al., 1993; Sevinc and Berkman, 2020). Cybersickness arises when the visual and postural information mismatch, although other theories have also been suggested (Rebenitsch and Owen, 2016). The primary method to reduce cybersickness in VR applications is to reduce the lag between the user's movement and the change they see. The speed at which the software can render the VE is usually represented as frames per second (FPS). The recommended minimum FPS for users' comfort is 75 FPS, but developers try to aim at 90 FPS or higher.

VR suffers from other perceptual problems, such as errors in distance judgments (Kelly et al., 2022), limited field of view requiring participants to turn their heads rather than just look sideways, potential visual blurring and eyestrain, and some people are simply unable to use the binocular cues. HMDs can also be uncomfortable, and wearing them might change the overall relaxation levels one can achieve.

1.3.2 Virtual forests as a platform for research

One of the outcomes of the multitude of research on forest bathing is that not all forests have the same restorative power (Martens et al., 2011; Sonntag-Öström et al., 2014; Simkin et al., 2020). Forests vary in their restorative powers due to different tree compositions, structures, or topologies. Forest interiors positively impact stress reduction and attention restoration, whereas looking at a forest from the exterior or being at its edge does not (Van den Berg et al., 2014; Chiang et al., 2017; Takayama et al., 2017)). Different tree species seem to have different effects (Guan et al., 2017), and older forests provide more considerable benefits (Simkin et al., 2020). Other researchers observed that individual preferences are tied to a specific natural environment (Gao et al., 2019). Knowing the exact features important for forest bathing to work can provide forest services with important pointers in managing forests in their countries. The necessity to study such impacts was already suggested (Frost et al., 2022), but such control over nature is impossible.

Despite the challenges outlined above, VEs present an incredible opportunity to use virtual copies of real forests (so called digital twins) for forest bathing research. In VEs, researchers can fully control the environment, set the structure and tree composition as needed, change the soundscape of the experience, control the weather or change the lighting conditions as necessary. Virtual administration also standardizes the experimental procedure, diminishing the varying experiences which can occur throughout real-world studies. And while the costs of hardware capable of running these experiences can be relatively high, these are smaller than the personal and travel costs associated with forest bathing research in real-world locations.

For these reasons, using forests' digital twins is a tempting prospect for forest bathing research. However, if we base our real-world decisions on the results obtained in virtual worlds, we must understand exactly how the virtual experience differs. Although some studies have examined virtual forest bathing (for an overview, see Frost et al. (2022)), and some compared forest bathing in virtual environments to that of the real world (Mattila et al., 2020; Reese et al., 2022; Ünal et al., 2022), to our knowledge no study used exact digital twins.

1.4 Aims

Our pilot study matched the procedure of real-world forest bathing as closely as possible to the VR administration to determine each platform's benefits and provide future guidelines for VR research into forest bathing. Our goal is to investigate the potential of using digital twins of forests as an on-demand substitute for real-world forest bathing and use them to explore the individual features of real forest bathing in a fully controlled environment. To answer these questions, we wanted to understand how real forest bathing and forest bathing in a digital twin compare in affecting a person's relaxation and increasing their positive and reducing their negative emotions. Do virtual and real forests work the same way for forest bathing purposes? And what potential differences between the real and virtual administration determine virtual forest bathing's efficacy?

2 Methods

Participants in this study spent half an hour bathing in either a real or virtual forest. Some participants visited both versions across two separate sessions. We kept the procedures between the real and the virtual forest bathing as close to one another as possible. We collected psychometric measures of emotional state and relaxation and analyzed observed gains. The environments were an actual forest location close to the university campus and its digital twin built-in Unreal Engine and visited by participants in VR.

2.1 Real forest

The forest was in Roztocký háj natural reserve near the Czech University of Life Sciences campus. The experiment occurred during the vegetation growing season in an acidic oak-hornbeam forest composed mainly of common hornbeam (*Carpinus*

FIGURE 2
Demonstration of the virtual and the real forest bathing sessions. Subfigures show the sitting part of the virtual **(A)** and real-world **(B)** sessions.

betulus) and common oak (*Quercus robur*). The trees were approximately 60–80 years old, and there was only a little undergrowth (see Figure 2.B.). The forest was easily accessible to the participants. However, because of its proximity to densely inhabited areas, there were sometimes audible traffic noises or human presence (e.g., kids' voices in the distance).

2.2 Virtual forest

To match the forest composition and structure as best as possible, we scanned the location where the real-world forest bathing would take place using LiDAR technology and converted it into its digital twin.

2.2.1 LiDAR

Light Detection and Ranging (LiDAR) is a remote sensing method using a pulsing laser to measure object distances. LiDAR creates a series of points in 3D space, the so-called point cloud (see Figure 1, Subfigure A), designating positions where the laser hits an obstacle.

The LiDAR data were acquired by GeoSLAM ZEB Discovery mobile mapping solution. The assembly consisted of GeoSLAM ZEB Horizon handheld laser scanner using a zigzag walking pattern, ensuring coverage of all stems present in the area from multiple sides. Additional photogrammetric data were acquired to estimate the individual tree species.

After the acquisition, the data were processed into the point cloud using GeoSLAM software. The point cloud was classified into ground and non-ground. The ground points were used to construct a terrain model with a 1-meter resolution. Tree information was estimated from a subgroup of points between 125 and 135 cm above the ground, as 130 cm is the common forestry agreed height determining tree diameter in forest inventories. The points were fitted with a circle function using a random sample consensus (RANSAC) method. The center of the fitted circle determined the tree's position; its diameter was the tree's diameter. The highest point above the fitted circle in a radius of 1 meter is considered the tree's height.

2.2.2 Creating the digital twin

The digital twin of the forest was made in Unreal Engine 4.27. We used the information extracted from the point cloud to set the locations of tree models using custom scripts (public release in preparation). The semi-automated process places desired models at their appropriate locations and sets each tree's width and height to match its real-world counterpart.

The surrounding area, which participants could not directly visit, was populated with models of trees and shrubs of varying heights to create a sense of an ongoing forest. The forest floor was populated with meshes of fallen leaves, branches, and vegetation to provide a pleasant and varied visual stimulation similar to the real forest environment. Ambient audio was recorded at the real forest site from three points making a triangle shape approximately 10 meters apart and placed at similar locations in the virtual environment to form spatial audio. The lights were dynamic, and wind simulation was applied to the vegetation to provide a simulation of a real site as close as possible. The procedure can be seen in Figure 1.

2.2.3 Hardware

The experiment was administered using HTC Vive Pro Eye on a Windows 10 PC. The PC was equipped with a Core i7 processor, 32 GB of DDR4 RAM, and an RTX 3080 graphics card.

2.3 Questionnaires

We assessed participants' emotional states using the Positive and Negative Affect Schedule scale (PANAS) (Watson et al., 1988), similar to previous work (Mattila et al., 2020; Reese et al., 2022). PANAS is one of the most common tools to assess immediate affect. It has 20 questions, half of which assess the presence of positive emotions (e.g., "enthusiastic") and half assess negative emotions (e.g., "distressed"). PANAS has three main output scores - positive, negative, and hedonism, which is a simple difference between the positive and negative scores. For this pilot study's simplicity, we primarily analyzed the hedonism score, which combines negative and positive measures.

We measured the perceived beneficial outcomes of the participants by the Restoration outcome scale (ROS, Korpela et al., 2008). The participants responded on a seven-point scale (1 = not at all, 7 = completely) to 6 items assessing relaxation ("I feel calmer after being here.", "After visiting this place, I always feel restored and relaxed.", "I get new enthusiasm and energy for my everyday routines from here."), restoration ("My concentration and alertness clearly increase here."), and clearing of one's thoughts ("I can forget everyday worries here," "Visiting here is a way of clearing and clarifying my thoughts").

We assessed participants' level of cybersickness with the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). SSQ contains 16 questions addressing various symptoms of cybersickness, such as general discomfort, fatigue, nausea, blurred vision, or difficulty concentrating. Participants self-assess the presence of these symptoms on a scale of 1–4 (none, slight, moderate, and severe). SSQ provides a total score and three individual subscales - oculomotor (e.g., eyestrain, blurred vision), disorientation (e.g., dizziness and vertigo), and nausea (e.g., general discomfort, stomach awareness). We worked with the nausea subscale. Participants marking at least two symptoms on the SSQ nausea scale to be present or one symptom to be significantly present were labeled as feeling sick.

2.3.1 Demographic measures

We asked the participants about their age, gender, highest reached level of education, size of the town they spent most of their childhood in, their professional and leisure interest in forestry, botany, and other related fields, and how many times a week they usually visit forests (differing per season of the year). We also asked how they rated their physical and psychological health in the last two weeks, how well they physically felt at the moment, and how stressful their day was so far.

2.4 Procedure

Participants were pseudorandomly assigned (based on weather and time availability) to start in either the virtual or the real forest. Several weeks later, they were invited back to experience the other environment. Unfortunately, many participants could not attend the follow-up session.

2.4.1 Forest session

The forest where the experiment took part was located 2 km from the university campus. The participants either met the researchers at a parking lot at the edge of the forest or the researcher drove them from the university campus.

Upon starting the session, participants signed informed consent and filled in the questionnaires - demographics, attitudes toward forests, PANAS-SF, ROS. Researcher then led them to a designated place in the forest (approximately 300 meters from the meeting point) and asked them to turn off their cell phones or other distracting devices. The participants were asked to sit for 15 min on a provided camping chair with back - and armrests and relax while observing the forest, and the researcher left. An illustration of this stage can be seen in Figure 2, subfigure B.

The researcher returned after 15 min. Participants then filled in a ROS and were asked to relax in the forest for another 15 min, slowly walking in an area approximately 4 meters from the chair. The walking area was limited to keep the experience close to the virtual session. Again, the researcher walked away and returned after 15 min.

In the end, participants filled in the final PANAS-SF and ROS and two questions exploring how distracted they were by people or other elements during the experiment. Finally, the researcher led the participants back to the initial meeting point where the session ended.

2.4.2 Virtual session

The virtual forest bathing took place in an experimental room on a university campus. The procedure was analogous to the one in the real forest, except participants also filled in the simulator sickness questionnaire (SSQ) (Kennedy et al., 1993) after the experiment. The researcher also continuously checked with the participants to see whether they felt well. If participants reported increased levels of nausea, the experiment would be stop prematurely. No participants reported nausea during the session, although some reported it after the experiment had ended.

TABLE 1 PANAS hedonism and ROS scores throughout the session.

		Before session		After seating		After walking		
Questionnaire	Environment	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	N
PANAS hedonism	Real forest	12.90 (9.87)	-3, 29	-	-	14.27 (12.67)	-6, 32	15
	Virtual forest	17.20 (6.34)	4, 32	-	-	18.25 (7.40)	4, 35	20
ROS score	Real forest	24.87 (8.19)	9, 40	28.53 (7.26)	18, 40	29.00 (7.80)	17, 41	15
	Virtual forest	28.05 (5.98)	19, 42	30.65 (6.47)	17, 41	29.20 (5.91)	19, 37	15

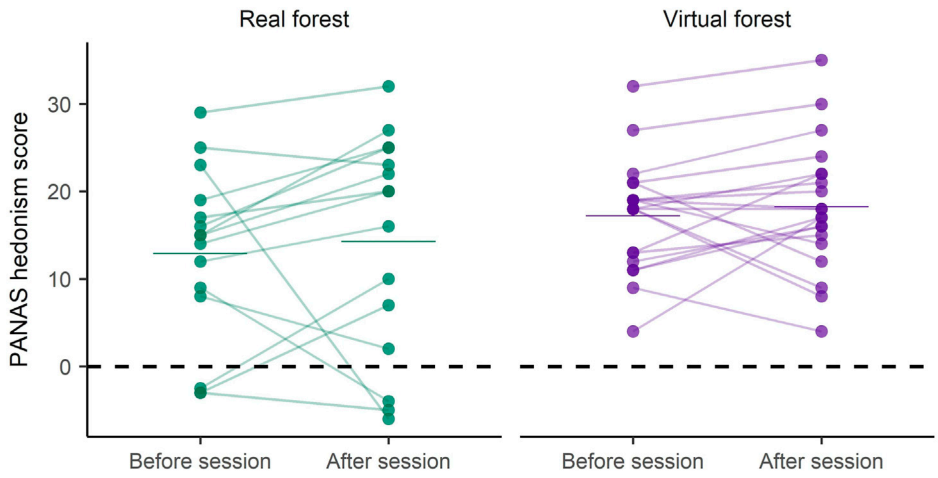

FIGURE 3
Individual change in participants' emotional state (PANAS hedonism score) split by virtual and real forest sessions. Each line represents an individual change, and horizontal lines in the graphs are mean values. The dashed horizontal line at 0 signifies a split between overall positive and negative emotions (above zero being overall positive).

Before the walking part of the experiment, the researcher removed the chair to avoid potential collision and held the cable connecting the VR HMD with the computer to prevent the participant from stumbling over it. The virtual session's illustration can beseen in Figure 2, subfigure A.

2.5 Ethics committee

Ethics Committee of the Czech University of Life Sciences Prague found no contradiction against principles of ethics and approved the research.

2.6 Participants

Twenty-five participants (mean age = 30.7, SD = 9.5, range: [19, 54.50]; 11 females, 13 males, 1 other) attended the study. Ten participants attended both conditions Five participants in the VR condition did not fill out the final ROS questionnaire, and two participants did not fill in the final SSQ questionnaire due to the researcher's oversight. No participant wished to stop the experiment due to nausea, although some reported symptoms after the session had ended.

3 Results

All analyses were conducted in R (R Core Team, 2017). Graphs were created using a *ggplot2* package (Wickham, 2009) and mixed model analyses using *lmer* package (Bates et al., 2015).

3.1 Overall effects

Descriptive statistics of participants' emotional state (PANAS hedonism) and relaxation (ROS) throughout the experiment can be found in Table 1. Due to the small number of participants in our sample, we have also conducted power analyses to demonstrate relatively low power of our analyses and the

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TABLE 2 Calculated effect sizes and power for t-test pairwise comparisons for the two main outcome measures.

Questionnaire	Environment	t	df	p-value	Cohen's D	Cohen's D 95% CI	Power
PANAS positive	Real forest	1.828	14	0.089	0.233	-0.032, 0.499	0.217
	Virtual forest	- 0.310	19	0.760	-0.045	-0.341, 0.250	0.033
PANAS negative	Real forest	0.313	14	0.759	0.122	-0.679, 0.923	0.018
	Virtual forest	-1.528	19	0.143	-0.407	-0.968, 0.154	0.544
ROS score	Real forest	2.074	14	0.057	0.516	-0.026, 1.059	0.600
	Virtual forest	0.868	14	0.400	0.242	-0.338, 0.822	0.226

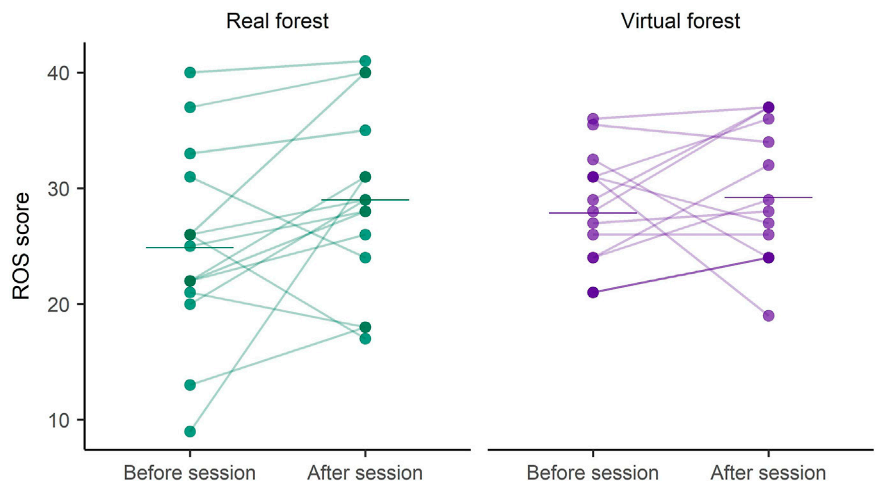

FIGURE 4
Individual change in relaxation (ROS score) split by virtual and real forest sessions. Each line represents an individual change, and horizontal lines in the graphs are mean values.

increased likelihood of type II error. These analyses are summarized in Table 2.

3.1.1 Emotional state

Although we saw a slight improvement in participants' emotions after both VR (an increase of 1.05 ($SD = 6.05$)) and real forest sessions (an increase of 1.37 ($SD = 10.90$)), this improvement was not statistically significant ($t(34) = 0.84$, $p = .405$, $Cohen's\ D = 0.13$). We have not found a difference between either positive ($t(34) = 0.96$, $p = .343$, $Cohen's\ D = 0.10$) or negative affect ($t(34) = -0.41$, $p = .685$, $Cohen's\ D = -0.10$). The change in hedonism can be seen in Figure 3.

3.1.2 Relaxation

We saw a significant increase in participant's relaxation from the start of the experience (26.69 ($SD = 7.08$)) to the end (29.10 ($SD = 6.80$)) ($t(29) = 2.16$, $p = .039$, $Cohen's\ D = 0.40$). This increase occurred mainly during the first seating part of the forest bathing ($t(34) = 3.08$, $p = .004$, $Cohen's\ D = 0.44$) and there were no significant changes in relaxation levels during the walking part ($t(29) = 0.12$, $p = .902$, $Cohen's\ D = 0.02$). Changes in participants' relaxation can be seen in Figure 4.

3.2 Difference between environments

To investigate the impact of the different environments, we modeled the ROS scores using mixed effect modeling with participant as a random intercept and the order of the administration (before the session and after the session), the environment (real and virtual) and their interaction as fixed effects. We found that relaxation increased between administrations ($\hat{\beta} = 4.13$, 95% CI $[0.30, 7.97]$, $t(34.49) = 2.11$, $p = .042$), but

TABLE 3 Binary improvement from before the session to after forest bathing. Classifying participants as either benefiting from the experience or worsening.

Environment	Change in score	ROS score	PANAS hedonism
Real forest	Worsened	3/15 (20%)	5/15 (33%)
	Improved	12/15 (80%)	10/15 (67%)
Virtual forest	Worsened	4/15 (27%)	6/20 (30%)
	No change	1/15 (7%)	1/20 (5%)
	Improved	10/15 (67%)	13/20 (65%)

neither the environment ($\hat{\beta} = 2.41$, 95% CI $[-1.49, 6.30]$, $t(45.55) = 1.21$, $p = .232$) nor the interaction were significant ($\hat{\beta} = -2.60$, 95% CI $[-7.91, 2.71]$, $t(35.63) = -0.96$, $p = .343$), demonstrating some comparability of the experiences. There was slightly higher starting level of relaxation in the VR session, and although the effect size was reaching a medium threshold, the difference was not significant ($t(24.54) = -1.27$, $p = .215$, $Cohen's\ D = -0.45$)

3.2.1 Binary improvement

Looking at the purely binary assessment of whether participants improved or not in Table 3, we can see very comparable numbers between the virtual and the real forest. Approximately one-third of participants worsened or did not change in either emotional state or relaxation, while about two-thirds benefited from the experience.

3.3 Demographic differences

3.3.1 Gender effects

We have observed a significant effect of gender on the PANAS hedonism score change ($t(28.19) = 2.14$, $p = .041$, $Cohen's\ D = 0.72$), although the change in ROS scores did not reach significance despite the medium effect size ($t(24.44) = 1.64$, $p = .114$, $Cohen's\ D = 0.58$).

We analyzed the change in PANAS hedonism using analysis of variance with gender, environment, and their interaction as predictors. We have found only a trending effect of gender on the change in emotional state ($F(1, 29) = 3.99$, $p = .055$, $\hat{\eta}^2_G = .121$, 90% CI $[.000, .318]$), although the effect size was large. The interaction between gender and the environment was not significant ($F(1, 29) = 0.48$, $p = .494$, $\hat{\eta}^2_G = .016$, 90% CI $[.000, .157]$). Overall, it seems that women in our sample benefited from the experience, and men seemingly did not enjoy either environment.

In ROS score, neither gender ($F(1, 25) = 2.38$, $p = .136$, $\hat{\eta}^2_G = .087$, 90% CI $[.000, .292]$) nor the interaction reached significance ($F(1, 25) = 0.67$, $p = .420$, $\hat{\eta}^2_G = .026$, 90% CI $[.000, .195]$) and the effect sizes were overall small, suggesting that the levels of relaxation achieved were comparable between genders.

3.3.2 Age effects

To investigate the potential effects of age on the benefits gained in either environment, we modeled the change of PANAS as an effect of age, environment, and the interaction between them. The model was not overall significant ($R^2 = < .01$, $F(3, 31) = 0.01$, $p = .998$), suggesting that neither age nor the interaction between age and environment was significant. The same result was obtained by modeling the level of achieved relaxation ($R^2 = .12$, $F(3, 26) = 1.13$, $p = .354$).

3.4 Cybersickness

We were also interested in what effects cybersickness would have on the efficacy of the experience. While only two participants verbally reported feeling sick, six participants reported multiple symptoms on the SSQ nausea subscale ($M_{SSQ\ nausea} = 1.28$ ($SD = 0.36$)).

Modelling the SSQ nausea score as a predictor of PANAS change after the VR experience with linear regression returns a significant model ($R^2 = .24$, $F(1, 16) = 5.12$, $p = .038$) with a significant and negative effect of cybersickness on change in affect ($b = -8.58$, 95% CI $[-16.61 - 0.54]$, $t(16) = -2.26$, $p = .038$). Modeling ROS scores as a function of SSQ score also gives a significant fit ($R^2 = .38$, $F(1, 12) = 7.44$, $p = .018$) with negative effect of cybersickness on the final score ($b = -10.66$, 95% CI $[-19.18 - 2.15]$, $t(12) = -2.73$, $p = .018$). These results should be, however interpreted cautiously due to our small sample size as the effect might be solely driven by the participants reporting multiple cybersickness symptoms.

3.4.1 Cybersickness and demographics

There was no significant difference in the cybersickness levels between the genders ($t(0.21) = 0.06$, $p = .951$, $Cohen's\ D = 0.033$)

TABLE 4 Binary comparison of change in relaxation and emotional state in participants who attended both sessions.

Real forest	Virtual forest	ROS	PANAS hedonism
Improved		2/7 (10%)	5/10(10%)
Worsened		1/7 (10%)	2/10(10%)
Improved	Worsened	2/7 (10%)	2/10 (10%)
Improved	No change	1/7 (10%)	-
Worsened	Improved	1/7 (10%)	1/10 (10%)

nor was there a significant effect of age ($R^2 = .02$, $F(1, 16) = 0.29$, $p = .596$).

3.5 Individual change

One of our main questions was about the individual comparability of the results. If a person benefited from the real forest bathing, did they also benefit from the virtual one?

Looking at the binary improvement in PANAS scores, we saw that seven participants benefited similarly from the virtual and the real forest (five improved, two worsened), two worsened in VR. One participant improved in VR compared to the real forest. Regarding the relax scores, four participants performed similarly in both environments, two worsened in VR and one improved in VR compared to the real forest. For an overview, see Table 4.

Modeling the change in PANAS in VR as a function of change in the real forest using linear regression did not build a strong model ($R^2 = .08$, $F(1, 8) = 0.66$, $p = .441$), and neither did predicting relaxation in VR based on real-world data ($R^2 = .03$, $F(1, 5) = 0.17$, $p = .698$). Overall, it seems that the benefits gained in VR are not fully comparable to those from the real forest, but more data is needed to be certain.

However, given what we know about the cybersickness, we also investigated how it might have affected the results and the transferability of the experience.

Modeling the PANAS change in VR as a function of the change in the real forest and SSQ nausea score gives a stronger model than the one without SSQ ($R^2 = .44$, $F(1, 8) = 2.70$, $p = .135$) and using a Likelihood Ratio Test shows that this model is significantly better ($\chi^2(1) = 1.93$, $p = 0.026$). Similarly, the model predicting ROS change in a virtual forest as a function of the ROS change in the real forest with SSQ returns a strong, albeit not significant model ($R^2 = .64$, $F(1, 5) = 3.56$, $p = .129$) that performs better than the model without SSQ ($\chi^2(1) = 6.92$, $p = 0.009$). This demonstrates that cybersickness can be a strong modulator of the VR experience and should be considered when running similar experiments in the future.

4 Discussion

Surprisingly, we could not demonstrate the clear and impactful benefits of forest bathing on improving the positive and decreasing the negative emotions in either condition. We observed a significant but small to medium effect of the experience on participants' relaxation. Our current data suggest no significant difference between the virtual and the real forest, and most participants react to both environments similarly, but a study with larger statistical power is needed to be certain. There was no effect of age, but we found a significant effect of gender, with men in our sample benefiting less from experience. Furthermore, we observed a negative effect of cybersickness on gained benefits in VR, with people who reported multiple symptoms worsening in their relaxation and emotional state.

4.1 Restoration outcomes

Compared to other studies investigating the effects of virtual forest therapy, the lack of therapeutic effect could be surprising, especially when considering the real forest location. Previous research overwhelmingly supports the idea of the positive impact of forest bathing on the human psyche (see Antonelli et al. (2022) for an umbrella review of 16 systematic reviews). Frost et al. summarized 21 studies using some form of natural immersion in VR, and all but one found positive effects (Frost et al., 2022). Although we have found a significant increase in relaxation, our results are not as straightforward as the current literature would make us think.

One of the main reasons for the lack of significant results can be the small sample and the overall low power of our analyses. While the effect sizes for the relaxation ranged from small to medium in both environments, we could not find significant effects in most comparisons. To assess these effects properly, we would need at least twice the number of participants in most scenarios, and to properly assess the small effects, more than one hundred participants would be needed. Mixed effect modeling performed by *lmer* also does listwise deletion in case of missing data, which might lead to more underpowered results in these analyses.

We found overall smaller effects than those reported by other researchers. Reese et al. (2022) found effects twice as large for the PANAS improvements and Mattila et al. (2020) also found large effect sizes in PANAS improvements. In our sample, decrease of PANAS negative affect in VR reached a medium effect size, while other comparisons were small or none. Needless to say, the confidence intervals of the effect size were relatively large due to the large variability and small sample size, so a follow-up study is needed.

Beyond the low power, overall small differences between pre- and post-test scores might have been caused by the fact that the participants were relaxed even before the start of the experiment, so there was little to improve. Participants in the virtual forest started more relaxed and with more positive affect. Therefore, it is possible that we did not reveal substantial differences because of the ceiling effect. Applying some of the stress-inducing tasks before the experiment (Skoluda et al., 2015) might be helpful when conducting future studies. Furthermore, measuring physiological outcomes, such as electrocardiography, electrodermal activity, or cortisol levels, might bring complementary evidence to the self-rated measures.

The difference between benefits gained by women and men is surprising and contrasting to previous studies (Frost et al., 2022). In our study, men, on average, worsened their emotional state in both conditions and decreased their relaxation in the virtual forest. While they slightly increased relaxation in the real-world forest, overall, their experience seemed significantly worse than that of women. We found no significant difference in cybersickness. While some studies have also reported differences between genders (Kotera et al., 2022), they report that both genders improved, just women benefited more. In our case, the experience seemed detrimental to men's well-being. Whether this was due to our specific procedure or forest will have to be addressed in the future.

4.2 Real forest

While most studies report the overall group improvements after forest bathing, looking at individual performances, we saw multiple participants who did not enjoy the experience. Some participants reported they did not enjoy their time in the forest due to real-world complications, namely insects, other people passing, or weather conditions. Also, although not commonly addressed, some people might feel intimidated and threatened by exposure to a real forest. Forests might represent a novel and unknown environment where they do not feel safe. Others might like the forests but anticipate unpleasant encounters (ticks, mosquitoes, or snakes).

4.3 Virtual forest

One problem of the VR administration is cybersickness. Our results corroborated the results obtained by previous authors (Reese et al., 2022) to a certain degree. We demonstrated a relationship between the level of nausea and the benefits gained from the VR forest session and almost all participants reporting two or more symptoms felt less relaxed after the experience. Measuring and reducing cybersickness levels, for example, by reducing the time spent in the VR, seems prudent in future studies, although this might limit the transferability of results between real and virtual forest bathing.

Although our VR environment reflected the distribution and size of trees in the real forest, capturing all the details was impossible, especially on a small scale. Since the participants spent 15 min walking in a small area of 4–5 m, they focused more on the details. They spotted the imperfections of the VR environment, such as the absence of small animals (e.g., insects) or mushrooms. Furthermore, the respondents lacked other sensory perceptions, such as the smell of the forest. It was also impossible to touch a tree or ground or hear the leaves rustling when walking.

Another difference in our procedures that might have affected the results was the duration of the experience. Comparable studies generally put participants in the simulation for 5–10 min (Mattila et al., 2020; Reese et al., 2022), others for up to 20 min (Ünal et al., 2022), while our participants spent half an hour in VR—15 min of sitting followed by 15 min of walking. We saw a relaxation increase during the sitting period, but no further changes occurred during the walking. The longer duration could lead to negative ruminations, increase the likelihood of cybersickness symptoms, or increase boredom. Previous studies also differed in the employed movement techniques. While most VR studies did not allow participants to walk, others usually used a controller. The active movement should strengthen the effects in our implementation (Pretty et al., 2003), but to what extent these differences might affect virtual forest bathing is still unclear.

4.3.1 Fascination with VR

One potential confound of the short VR sessions' restorative power is its novelty. Some studies built virtual natural landscapes specifically for VR (Mattila et al., 2020), aiming to fascinate the participants. This approach cleverly uses the main benefits of the platform and creates a beautiful-looking environment that does not suffer from real-world ills. These environments calm and intrigue users, satisfying the core principles of the ART hypothesis (Kaplan and Kaplan, 1995), and there is a promising future in such applications. However, such environments may provide only short-term, not reproducible effects. So far, we have only a limited indication that the effects are still present after some time, as most studies, including ours, only test restorative power immediately after the experience (Mattila et al., 2020; Reese et al., 2022; Ünal et al., 2022). Whereas long-term forest bathing programs in the real world have been investigated (see Antonelli et al. (2022), for a review), no forest bathing over multiple sessions has been studied in VR. It is possible that after the initial brief excitement, the restoration power of the VR diminishes, which is why we saw lower power in our thirty minutes long sessions.

Few participants in our study also verbally reported disappointment with the virtual forest, which was related to their expectations. Participants complained that they could not see any forest animals and that even though they could hear birds, they could not see them. Although the situation was similar in the real forest (no animals were spotted, and birds remained above the tree canopy), participants did not report any disappointments. This is related to the results reported by Mattila (Mattila et al., 2020), who discussed the increased fascination with the VR environment compared to real forests.

4.3.2 Comparability between the platforms

Although we have not found significant differences between the conditions using mixed effect modeling, more data is needed to be certain. Nevertheless, our results show that people's experience is somewhat comparable between the virtual and real world. When participants liked or disliked their time in the real forest, they likely reported the same in the virtual one. And while some people benefited differently from virtual forest bathing, the change could be both negative and positive. We observed that all participants who had a worse experience in the virtual forest than in the real forest reported cybersickness symptoms.

However, we could not model the change in participants' relaxation or emotional state in virtual reality based on their experience in the real world. Whether this was due to our limited sample, cybersickness, them being tested on a different day with different stress levels, changes in procedure, or whether the participants' expectations about the technology and fascination with the virtual reality world led to different outcomes is yet to be determined.

4.4 Limitations

One of the main limitations is our small sample size and the limited number of participants who returned for the second session. As this study was conceived as a pilot exploration, we only had data from 25 (20 finishing VR and 15 real forest) participants, and only ten of them completed the entire experiment. For future studies, given the distribution of the effect sizes reported in other studies, we recommend that at least forty participants are included. Nevertheless, we believe that even this modest number demonstrates important results that opened new questions and informs researchers about how to update their research methodologies in similar scenarios.

Participants' self-selection for the second session could have also affected the results, although we saw no significant differences between participants who attended both sessions and those who came only once.

We would also like to allow the participants to explore the forest for a greater distance than only 4–5 m, but the VR HMD limits us. Especially in the virtual forest, some participants reported being bored during the walking session. Some also said they felt like they were in a cage because of the VR safety boundaries that appear when a user is close to the edge.

Although PANAS and ROS are commonly used in forest bathing studies (Grilli and Sacchelli, 2020), it is possible that they were not descriptive enough, and we could miss some subtle differences between the participants. A more detailed and widely used Profile of Mood Scale (Curran et al., 1995) might bring more insight because it has six different subscales (tension, depression, anger, fatigue, confusion, and vigor). In contrast, PANAS only distinguishes a score for positive and negative emotions (and their difference).

4.5 Practical implications for future studies

Based on our results, we recommend that future studies use more detailed self-report measures (such as POMS) and physiological measures suitable for use in real forest bathing (heart rate or blood pressure).

Data from at least forty subjects should be collected to reliably detect small to medium effect sizes of changes in relaxation and affect after real and virtual forest bathing sessions.

The inclusion of structured interviews after the experiences to determine what did not work in those participants who did not improve is also recommended. Since we identified a subgroup of participants who got worse results after being in the real forest, it would be interesting to explore whether and how they differ from other participants.

In the real forest setting, providing the participants with insect repellent and suggesting wearing long sleeve clothes might improve their experience and lower the distress of the subgroup of participants who feel threatened by bugs.

The virtual experience could be improved by wirelessly connecting the HMD with the computer to increase participants' freedom of movement. Also, minimizing the visual barriers of the VR space to something less obstructive could reduce feelings of being trapped. Graphical improvements can also be made. Trees can be modeled using photogrammetry to best capture the species composition. Scanning and importing detailed patterns of the forest undergrowth would increase the sense of real forest presence.

Furthermore, natural materials can be used to improve the experience in VR. For example, researchers could spread leaves and bark in the experimental area to provide the sensory feeling of stepping on a forest floor. This could also solve the absence of smell. Olfactory sensations can be supported by installing fresh branches or, especially in the exposition of coniferous forests, using natural essences in a diffuser.

5 Conclusion

We investigated the potential of using the digital twins not only as a substitute for real-world forest bathing but also as a research platform to promote easier and reproducible science to help to fill the forest bathing research gaps, especially comparing the effect of different forest types, density, topology, and composition of species. Our study provides a novel insight into using forest digital twins as a therapeutic and research platform for investigating forest environments for relaxation. We consider virtual reality a promising alternative to real forest research. However, a larger, more controlled study is necessary to determine the exact comparability between the experiences, investigate the effects of cybersickness, and control for potential confounds, such as fascination with the technology. We also opened a neglected topic of real forest bathing drawbacks and stressed the importance of the individual approach to the participants. Exposure to real forests might not be the best restorative environment for everyone, and a personally tailored virtual forest could provide a functional alternative.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Ethics Committee of the Czech University of Life Sciences Prague Kamycka 129, 16500 Praha-Suchdol Head of comitee: PhDr. Michal Lošťák, Ph.D lostak@pef.czu.cz. The patients/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

LH, MH, AH, and PS contributed to the conception and design of the study. PS collected and processed the LiDAR data of the real forest location. LH created the digital twin. MH and AH collected and digitalized the data. LH performed the statistical analysis and created the graphs. LH wrote the first version of the manuscript. MH, AH and PS wrote sections of the manuscript. All authors contributed to the manuscript revision, read, and approved the submitted version.

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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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