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Comparison between three different delivery technologies of virtual nature on psychological state related to general stress recovery: An experimental study

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ABSTRACT

Visiting nature has been shown to have several benefits for psychological state related to general stress recovery. However, for many people, access to nature is limited. Technological development has made it possible to deliver nature environments virtually. The present study examines the benefits of a same virtual nature (forest) environment delivered through different technologies on psychological state related to general stress recovery, more precisely, on restoration, current stress, subjective vitality, and affective response. The main focus is on comparing three different delivery technologies of virtual nature: TV (75″), VR headset (Meta Quest 2), and virtual nature room (30 m^2). The study applies a three-condition randomized trial with pre-post assessments and a crossover design, where 62 participants visited once in each condition for a 15-min exposure of virtual nature (360-degree video with congruent soundscape). The participants responded to psychological measures before and after each condition. Overall, participants' restoration increased, while current stress and negative affect decreased during the exposure. In comparison to the TV (control) condition, both the VR headset condition and the virtual nature room condition had a better impact on psychological state related to general stress recovery, as restoration and subjective vitality increased more. There were no statistically significant differences between the VR headset and virtual nature room conditions in any of the measures.

1. Introduction

1.1. The relevance of nature for psychological state related to general stress recovery

Reduced psychological well-being and prolonged stress are major health issues in present-day occupational and educational settings. Evidence from systematic reviews suggest that work-related stress imposes substantial financial burden on society (e.g., Hassard, Teoh, Visockaite, Dewe, & Cox, 2018) and is associated with detrimental health outcomes, such as a moderately elevated risk of coronary heart disease and stroke (Kivimäki & Kawachi, 2015). Reviews have shown that education-related stress negatively affects students' learning capacity, academic performance, sleep, and mental and physical health, which leads to lower educational and occupational attainment in the long-term (e.g., Pascoe, Hetrick, & Parker, 2020). Therefore, environments that can enhance psychological state and prevent stress are increasingly needed and should be easily accessible.

Research has shown that nature environments, in particular, can support the psychological state related to general stress recovery (cf. Dadvand et al., 2023; Nejade, Grace, & Bowman, 2022). Hartig, Mitchell, De Vries, and Frumkin (2014), in their review of reviews, reported that nature contact can increases restoration, stress-reduction, and feelings of energy, and decreases self-reported anxiety, fatigue, anger, and sadness. Nejade et al. (2022), in their systematic review, also report of the various psychological benefits of natural outdoor environments, including improved mental health, perceived well-being, affect, mood, vitality, perceived restoration, and stress reduction, as well as reduced depression and anxiety. Recently, regular green space exposure has been associated with lower pharmaceutical prescriptions and healthcare costs (Patwary et al., 2023; Turunen et al., 2023).

The restorativeness of nature environments is typically explained from the perspectives of the Attention Restoration Theory (ART) (Kaplan & Kaplan, 1989) and the Stress Recovery Theory (SRT) (Ulrich, 1983; Ulrich et al., 1991). The ART (Kaplan & Kaplan, 1989) posits that being in or looking at nature environments restores directed attention and

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performance. The ART suggests that cognitive tiredness results from directed attentional fatigue, which can be restored in such environments that provide: an effortless and sufficient fascination; perceptions of psychological or geographical distance from the ordinary routines; compatibility with personal preferences; and extension (i.e., coherence) with the characteristics of the environment.

The SRT (Ulrich, 1983; Ulrich et al., 1991), drawing from psycho-evolutionary theory, posits that nature environments that positively influence the feelings of survival, safety, and well-being have both psychological and physiological benefits. These benefits include positive outcomes in terms of stress recovery, affective states, and well-being. Urban settings, on the other hand, are seen to have opposing effects (Berman, Jonides, & Kaplan, 2008; Berto, 2014; Tyrväinen et al., 2014; Ulrich et al., 1991). It is widely established that nature environments are more beneficial than urban environments for psychological state related to general stress recovery.

Overall, there is a widespread consensus on the various health and well-being benefits of visiting and spending time in nature (cf. Konijnendijk, Devkota, Mansourian, & Wildburger, 2023), including benefits to psychological well-being (cf. Dadvand et al., 2023). However, urbanization, deforestation, limited access to nature, as well as the increasingly stressful work life suggest a growing need to study the possibilities of modern technology to deliver restorative nature environments. For many people, especially those living in urban areas, access or opportunities to visit nature in their living and working environments are limited and they might experience nature mostly through TV or other screens. This limits the various health and well-being benefits of nature (Cox, Hudson, Shanahan, Fuller, & Gaston, 2017). Therefore, in these situations, it is important to offer alternative forms of nature exposure. One novel solution for this, brought about by technological development, is virtual nature.

The purpose of the present study is to increase the understanding on the effects of virtual nature on psychological state related to general stress recovery (later in the text referred to as "psychological state"), more precisely, on restoration, current stress, subjective vitality, and affective response.

1.2. *Virtual nature for psychological state related to general stress recovery*

Virtual nature refers to solutions where a nature environment is delivered virtually by utilizing digital technology with varying levels of realism, immersion, and interactivity. There are several technologies and modalities that can be used to deliver virtual nature. In research, the most commonly used delivery technologies are computer or TV screens, projector screens, and virtual reality (VR) headsets (cf. Browning, Saeidi-Rizi, McAnirlin, Yoon, & Pei, 2021). These are usually implemented with either real imagery (360-degree video, 360-degree photo, panoramic photo) or computer-generated imagery, and sounds (Nukarinen et al., 2022). However, room-scale virtual nature or cave automatic virtual environment (CAVE) systems have been seldomly used in research (cf. Browning et al., 2021; Frost et al., 2022). Virtual nature can incorporate various sensory modalities, such as visual stimuli, auditory stimuli, olfactory stimuli, haptic stimuli, and thermal stimuli, as well as non-sensory modalities like ultraviolet lights or near-infrared radiation. They may also include action-oriented modalities, such as exploration or walking (Nukarinen et al., 2022). Studies indicate that virtual nature benefits psychological well-being most effectively when both visual and auditory stimuli are utilized (Litleskare, MacIntyre, & Calogiuri, 2020). There are also several different methods for creating virtual nature material, such as video-game development technology, 360-degree cameras and microphones, as well as different software for post-production (Litleskare et al., 2020). As these are not in the scope of the present study, we refer the interested reader to the work by Litleskare et al. (2020).

Typically, virtual nature is delivered in non-natural settings, such as indoors, and are designed to act as surrogates (rather than replacements) for actual nature, especially where access to nature is not available. Such settings may include indoor settings such as workplaces, educational facilities, hospitals, elderly care homes, and prisons, as well as settings where relaxation and restoration from stress is needed, like airports or healthcare centers' waiting rooms. Barriers such as lack of access rights or personal physical or mental disabilities might also limit nature visitations. In such cases, virtual nature could be used to simulate experiences similar to those offered by actual nature, potentially enhancing psychological state (Browning, Mimnaugh, Van Riper, Laurent, & LaValle, 2020; Mattila et al., 2020; Nukarinen et al., 2020; Reese, Stahlberg, & Menzel, 2022; Takayama et al., 2022). Furthermore, solutions utilizing virtual nature are potential in promoting green exercise virtually (e.g., Calogiuri et al., 2018; Litleskare et al., 2022).

Research has shown that virtual nature can improve psychological state, as the findings from related systematic reviews generally demonstrate positive outcomes to self-reported measures of restoration, affective response, and stress relief (cf. Frost et al., 2022; Li, Ding, Zhao, Xu, & Wei, 2023; Spano et al., 2023), albeit some studies have found the actual nature to be more restorative (Browning, Mimnaugh, Van Riper, Laurent, & LaValle, 2020; Nukarinen et al., 2020) as well as produce better impacts on positive affect (Browning, Shipley, et al., 2020) than its virtual counterpart. Li et al. (2023) noted that the immersion level of the technology can influence these outcomes. Immersion level refers to the extent the technology is capable of delivering an inclusive and extensive surrounding and vivid illusion of reality to the senses of a human participant (Slater & Wilbur, 1997). Li et al. (2023), following the definition for technological immersion[1] by Slater and Wilbur (1997), classified technologies into low (e.g., TV screen), medium (e.g., CAVE), or high (e.g., VR headset) immersion level technologies. Their classification was based on self-established criterion drawn from prior literature, which considered the projection devices, level of visual isolation, and motion capture but not different sound systems. For example, low immersion level TV screen provides non-surround projection without visual isolation from physical reality, medium immersion level CAVE system provides surround projection but limited visual isolation from physical reality, and high immersion level VR headset provides surround projection and complete visual isolation from physical reality. For further details, we refer the reader to Li et al. (2023, p. 4). Li et al. (2023) also reported that medium immersion level technologies generally produce larger effects on positive affect compared to low and high immersion level technologies. It could be that high immersion level technologies might make people feel uncomfortable, especially if they feel cybersickness symptoms.

Previous research on the impacts of virtual nature on psychological state have been conducted with different immersion level technologies. The earliest of these studies were conducted with photograph slideshows (Ulrich, 1981). Since the number of virtual nature studies started increasing in the decade 2000s (Browning et al., 2021), TV screens (low immersion level) have been a popular choice of technology. Studies have suggested TV screens' potential benefit for psychological well-being and cognitive functioning (e.g., Friedman, Freier, & Kahn, 2004; Friedman, Freier, Kahn, Lin, & Sodeman, 2008). More recently, studies have used more advanced and more immersive technologies, such as VR headsets

[1] Note that the definition of immersion by Slater and Wilbur (1997) and Li et al. (2023) only considers technological immersion, that is, immersion as a property of a technology. Immersion could also be defined as a completely psychological phenomenon. One definition for psychological immersion is "a state of deep mental involvement in which the individual may experience disassociation from the awareness of the physical world due to a shift in their attentional state" (Agrawal, Simon, Bech, Bærentsen, & Forchhammer, 2019). In the present study, we refer particularly to the technological immersion when we write about different immersion level technologies. Overall, there is no consensus on the definition of immersion (Agrawal et al., 2019).

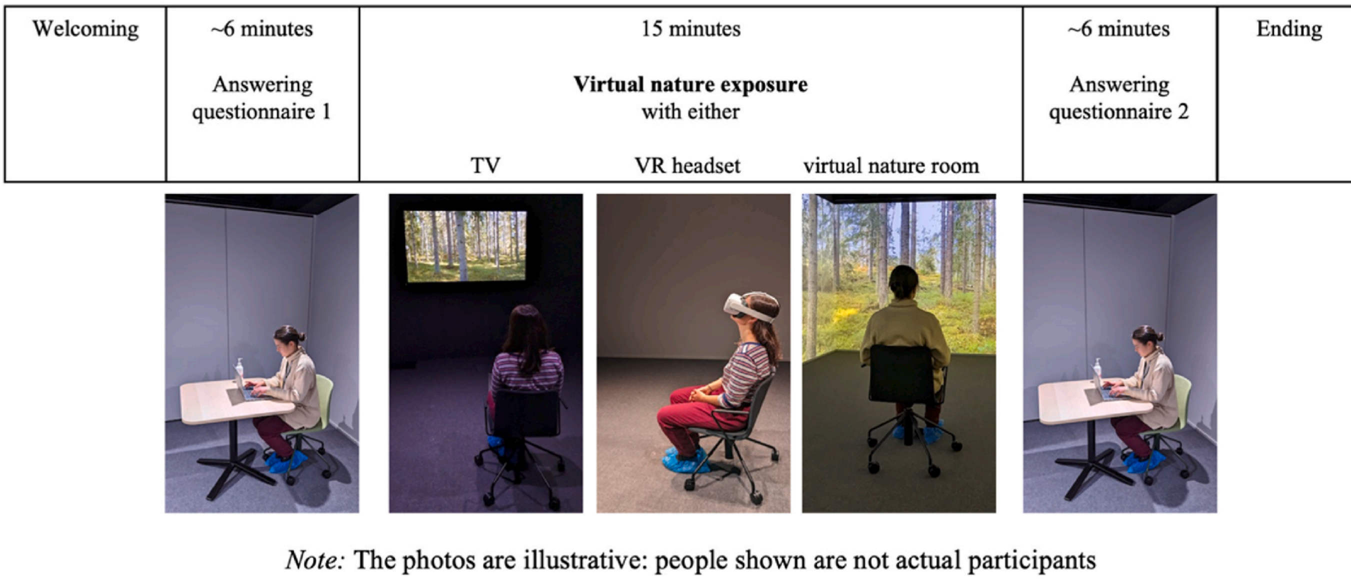

Fig. 1. The experimental setting. For higher resolution and wider images, see SM.C.1, SM.C.2, SM.C.3, and SM.C.4.

and room-scale virtual nature. However, TV or similar screens have also remained a popular technology (Browning et al., 2021). For example, recently Ojala et al. (2022) found that a nature video viewed from a TV screen with accompanying audio had more restorative effects than nature sound alone.

Prominent studies investigating VR headsets' (high immersion level) impacts on psychological state include Browning, Mimnaugh, Van Riper, Laurent, and LaValle (2020), who investigated the effects of 6-min exposure between outdoor nature, VR headset with 360-degree nature video and sound, and indoor setting without nature. They found that both types of nature exposures benefit positive affect and perceived restoration in comparison to an indoor setting without nature. Yeo et al. (2020) compared the effects of 5-min virtual nature exposure (video and sound) between a TV screen, a VR headset with 360-degree video (360-VR), and a VR headset with computer generated nature (CG-VR). They found a significant decrease in negative affect and increase in positive affect across conditions. Further, there was no difference between conditions in negative affect but greater increase in positive affect in the CG-VR over the TV and 360-VR conditions. Knaust et al. (2022) compared the effects of 5-min virtual nature exposure (video and sound) between a VR headset with 360-degree video, a computer screen, and no video/sound condition. They found that perceived relaxation was significantly higher with VR headset than a screen. Liszio, Graf, and Masuch (2018) came to a similar conclusion in terms of positive and negative affect. Mattila et al. (2020), utilizing VR headset with a computer-generated nature and soundscape, found an increase in perceived restoration, subjective vitality, and positive affect, as well as a decrease in negative affect after a 5-min virtual nature exposure.

The number of studies utilizing room-scale virtual nature (medium immersion level) is limited. In the seminal work by Annerstedt et al. (2013), 15-min virtual nature exposure in a CAVE system lead to *physiological* stress recovery, but only when the visual nature was accompanied with a soundscape, silent condition not having this effect. Shin, Browning, and Dzhambov (2022) conducted a study using a CAVE-like system, where participants were exposed to a 6-min virtual scene of a busy café. This virtual environment had different conditions related to the view through a window and the presence of scents. They found that conditions with either a closed window or an open window were more restorative than a condition without any window. However, they also found that the open window condition, which included sounds and smells of nature, was not more restorative than the closed window condition. Takayama et al. (2022) observed a significant decrease in negative affect and a significant increase in perceived restoration after a 20-min virtual nature exposure utilizing a room-scale virtual nature with video projection on three walls and the ceiling. As an addition to most other studies, they also used scents besides video and sound.

Overall, it seems that multisensory experiences (i.e., video with sound) offer better benefits than presenting visual or audio material alone. In addition, the immersion level of the technology has a role on the outcomes. High immersion level technologies have usually demonstrated better effects on psychological state than low immersion level technologies, but the body of comparative research across different immersion level technologies remains sparse. To our best knowledge, studies comparing low, medium, and high immersion level technologies are non-existent. In conclusion, the studies demonstrate the positive impacts of virtual nature for psychological state, but also highlight the need for further research (Frost et al., 2022; Li et al., 2023; Spano et al., 2023).

1.3. The present study

Although there have been positive findings on the ability of virtual nature to enhance psychological well-being, the findings have been partly contradicting, and overall, the research in this area is still limited (cf. Frost et al., 2022; Spano et al., 2023). The purpose of the present study was to increase the understanding on the effects of virtual nature on psychological state related to general stress recovery, more precisely, on restoration, current stress, subjective vitality, and affective response. The main focus was on comparing three different delivery technologies of virtual nature: TV (as control), VR headset, and virtual nature room. To our best knowledge, this is the first study to compare a room-scale virtual nature technology with a VR headset or a TV screen. In the immersion level classification by Li et al. (2023), TV is considered as a technology with low immersion level, virtual nature room would be a technology with medium immersion level, and VR headset would be a technology with high immersion level. Though it needs to be noted that as their classification did not consider different sound systems, it is not totally unambiguous in the case of the present study where different sound systems were used. Their classification also did not consider screen size, which can be an important aspect of visual immersion at least in the case of relatively small (≤30″) screens (Rigby, Brumby, Cox, & Gould, 2016).

The main differences between VR headset and virtual nature room (more detailed explanation in section 2.3.) are that VR headset allows a full 360-degree view including the ground below and the sky above, whereas the virtual nature room allows a room-scale four-wall 360-degree view without the ground and the sky. However, the virtual nature room frees the user from wearing a headset. Compared to a TV, both the virtual nature room and VR headset allow presentation of nature sites as a space rather than a limited scene and allow experiencing multiple viewpoints to the environment compared to a single viewpoint by a TV screen, thus enhancing the immersion necessary for attention restoration. TV was selected as a control condition due to its commonness and use in previous studies (e.g., Ojala et al., 2022; Yeo et al., 2020).

The used virtual nature material was a 15-min 360-degree forest video with congruent soundscape. In the lack of best practice and considering the wide variety of exposure durations used in previous studies (cf. Browning et al., 2021), the exposure duration was set to 15 min, as many previous related studies have also used the same duration (e.g., Anderson et al., 2017; Annerstedt et al., 2013; Ojala et al., 2022).

The main research questions were: 1. Does a virtual nature exposure benefit psychological state (measured by restoration, current stress, subjective vitality, and affective response)? and 2. What kind of differences there are between different technologies in the effectiveness for psychological state? Based on the research questions and the previous literature presented above, the following research hypotheses were formed:

Hypothesis 1. (1-tailed): A 15-min virtual nature exposure benefits psychological state across conditions: Self-reported positive affect, restoration, and subjective vitality increase, whereas negative affect and current stress decrease.

Hypothesis 2a. (1-tailed): An experimental condition with virtual nature room is a more effective setting than the control condition (TV) for psychological state.

Hypothesis 2b. (1-tailed): An experimental condition with VR headset is a more effective setting than the control condition (TV) for psychological state.

Hypothesis 3. (2-tailed): There is a difference between virtual nature room condition and VR headset condition in the effectiveness for psychological state.

2. Method

2.1. Study design and procedures

The study was conducted in accordance with the principles of the Declaration of Helsinki. The ethical review statement for the present study was given by the Ethics Committee for Human Sciences at the University of Turku. Before the study experiment, the participants were informed about the study, number of experimental sessions and their approximate length, the course of the experimental sessions, their rights as participants, and the goals of the study. The goals of the study were presented at a general level (i.e., to produce new knowledge about the effects of virtual nature and to offer practical insights based on this new knowledge). The course of the experimental sessions was presented in more detail including the welcoming procedure, responding to surveys, naming the different delivery technologies (names – not order or details), and the exposure time. Presenting this information is an ethical requirement, however, we aimed to present all information in a way that would not impact the results. All the participants gave their written informed consent. The experiment was carried out between March and early-June 2023 (springtime). The experiment took place in a virtual nature laboratory located in Helsinki, Finland.

The study included three experimental sessions for each participant, all of which had a different experimental condition, meaning that each study participant visited once in each of the three different conditions. All the three conditions took place in the same virtual nature laboratory. All experimental sessions followed the course shown in Fig. 1. Each participant took part in each condition alone, that is, there were no other participants in the same condition at the same time. The participants started the sessions at 8:00am the earliest and at 15:00pm the latest. By default, the researchers suggested a one-week interval between the sessions, but the participants could choose the dates of the experimental sessions according to their schedule and preference, bearing in mind that a minimum of one week was to be held between the sessions. While for the most, the one-week interval could be kept, for some it varied due to sickness or personal schedule. However, this was accounted for in the analysis.

The number of participants was based on power analysis, according to which the desired number of participants was at least 60 (for details, see Supplementary material (SM) SM.B). A 3 × 6 crossover design was used, where study participants were randomized to six different condition order groups (123,132,213,231,312,321: 1. TV, 2. VR headset, 3. virtual nature room).

Before the first experimental session, all participants answered a background questionnaire, a link to which was send to their emails. The background questionnaire included questions about nature relatedness, perceived stress, general health, technology use, immersive tendency, outdoor activities, etc. They were instructed to fill this less than one week before the first session. At the beginning of each experimental session, the participant was welcomed, asked to wash or disinfect their hands, put a Polar H10 heart rate sensor around the chest (to record ECG measures for a purpose of another study), and then guided to sit by a desk to fill the before-exposure questionnaire with a computer. After filling the questionnaire, the participant was guided into the experimental condition of the day and given related instructions. Then the participant went through a 15-min virtual nature exposure either with TV, VR headset, or virtual nature room condition. Participants did not know beforehand which condition was coming in each session, with the exception of the last session when there was only one condition left. After the virtual nature exposure, the participant was again guided to sit by a desk to fill the after-exposure questionnaire with a computer. The before- and after questionnaires included questions about perceived restoration, subjective vitality, affect, current stress, etc. The after questionnaire also included technology-specific questions related to the virtual nature condition (will be reported elsewhere). All the questionnaires were built with the Webropol survey tool (Webropol Oy, 2022). One session took approximately 35–40 min in total. The researcher never left the participant alone in the laboratory, but during the exposures the researcher was always quiet and out of sight.

2.2. Participants

A total of 63 participants volunteered to participate in the study. There was one drop-out (due to their work schedules), which lead to a sample size of N = 62. Of the 62 participants, 42 identified as woman and 20 as man (gender was asked with response options: Woman, Man, Transgender, Non-binary/non-conforming, and Prefer not to respond, but all respondents identified themselves as either woman or man). The age of the participants varied between 22 and 63 years old, the mean age being 40.42 years (SD = 11.01). The ethnic identity of all the participants was White. The majority (88.7%) evaluated their subjective health to be good or very good. The proportion (88.7%) was the same with quality of life. Physical fitness was evaluated to be good or very good by

Table 1
Sociodemographic characteristics of the participants.

Characteristic	*n*	%
Gender		
Women	42	67.7
Men	20	32.3
Age group		
22–29 years	12	19.4
30–39	20	32.2
40–49	15	24.2
50–63	15	24.2
Ethnic identity		
White	62	100.0
Highest educational degree		
University	52	83.9
University of applied sciences	4	6.5
Upper secondary school, gymnasium or equivalent	6	9.7
Closest green space[a] for recreation from home		
<200m	21	33.9
>200–500m	21	33.9
>500m – 1 km	15	24.2
>1 km	7	8.0
Current work/studies related to nature		
Yes	35	56.5
No	27	43.5

[a] Forests, parks, fields, meadows, bogs, bodies of water, and outdoor recreation areas with playgrounds.

56.5%. 83.9% had a university degree, and for 56.5% their current work or studies was related to nature. Exactly 50.0% evaluated their work or studies as quite stressful, very stressful, or extremely stressful. The participants were rather active in outdoor recreation, as during the warmer months (May–September) 91.9% visited green spaces 2–3 times or more per week, whereas during the colder months (October–April) the proportion was 71.0% respectively. For 91.9% the closest green space was less than 1 km from their home. Concerning technology use, 66.1% had at least tried a VR headset before but only one participant used them weekly. 40.3% had at least tried room-scale virtual solutions (without VR headset) but only two participants had any more experience. The key sociodemographic characteristics of the participants are presented in Table 1. The full descriptive statistics of the sample are presented in SM.A.

The exclusion criteria for participation were mainly related to the ECG measures (will be reported elsewhere) and were the following diagnoses: cardiac arrest, coronary artery disease, congestive heart disease, stroke, chronic obstructive pulmonary disease, asthma requiring maintenance treatment, hypertension, sleep apnea, epilepsy, alcoholism, or clinical depression. The exclusion criteria also included ongoing steroid medication, medication affecting heart rate, as well as smoking and drug use during the past month. Participants were asked to avoid excessive use of caffeine (more than three cups of coffee or equal), heavy physical exercise, and alcohol on the days of the experimental sessions. The participants were also asked to inform us and move their experimental session time, if there was less than 14 days from a positive COVID-19 test or related symptoms.

The participant recruitment procedure was approved by the Ethics Committee. To recruit the voluntary participants, several recruitment methods were used: advertising the study through different mailing lists, posting an ad of the study on physical and digital bulletin boards, handing out leaflets and organizing recruitment days in a campus area hosting a university and several national agencies. The participants came from different organizations within and outside the campus area. The participants did not receive any incentives such as economic compensation for taking part. Taking part in the study was completely voluntary, and no pressure, persuasion, or any power dynamics were involved in recruitment. For example, the institute where the study was conducted is not an educational institution, hence, none of the participants were students of the authors.

2.3. *The conditions and the virtual nature material*

2.3.1. *TV*

The TV (control) condition took place in a 16 m^2 square-shaped room equipped with a 75″ TV screen and a 4-channel surround sound system. The room was a closed but ventilated space. The TV allowed the participants to see about one fifth of the whole 360-degree view. During the exposure all the lights in the room were off. The participants sat on an office chair 2.6 m away from the TV. The viewing distance was determined based on the recommendation for TV viewing distance by THX and Home Cinema Guide (Home Cinema Guide, 2022). The participants were instructed to watch the TV for the whole 15 min and to not move around with the chair or rotate it. During the exposure, the researcher was sitting quietly in a corner behind the participant. Neutral colors were used in the room's interior decoration to minimize their effects on stress recovery during the experiment. For overview, see Fig. 1 and SM. C.1.

2.3.2. *VR headset*

The VR headset condition took place in the same room and the participants sat on the same revolving office chair as in the TV condition. The participants were instructed to not move the chair from its place, but they were allowed to rotate it in a calm manner and move their head around, allowing a full 360-degree view of the virtual nature (including the ground below and the sky above). The VR headset used in the study were Meta Quest 2, which have 6DOF, 1832x1920 resolution per eye, and positional sound system built directly into the headset (Meta, 2022). In the VR headset condition, the sounds were played directly from the headset, instead of the room's surround sound system. If the participant wore eyeglasses or contact lenses, they could decide whether or not to use those with the VR headset. To better accommodate eyeglass wearers, a glasses spacer was installed to the VR headset. Hygiene pads were used and changed after every use, and the headset was also disinfected after every use. During the exposure, the researcher was sitting quietly in a corner of the room. For overview, see Fig. 1 and SM.C.2.

2.3.3. *Virtual nature room*

The virtual nature room condition took place in a separate 30 m^2 rectangle-shaped room equipped with six video projectors and an 11-channel ambisonic sound system enabling a room-scale four-wall 360-degree virtual nature view with congruent soundscape. The room was a closed but ventilated space. During the exposure all the lights in the room were off. The participants sat on a revolving office chair in the middle of the room. They were instructed to not move the chair from its place, but they were allowed to rotate it in a calm manner allowing a four-wall 360-degree view of the virtual nature (not including the ground nor the sky). During the exposure, the researcher was sitting quietly behind the door, so that the participant could experience the virtual nature room by themselves. For overview, see Fig. 1 and SM.C.3.

2.3.4. *The virtual nature material*

The same 15-min audio-visual material was used across all the three conditions. The material included a static video with sound, that is, the viewer perspective did not move in the virtual nature. However, there was some movement of objects (i.e., tree branches slightly moving in the wind), which could make the virtual nature feel more 'life-like' (Litleskare et al., 2020). We decided to use a static video, as dynamic videos in which viewer perspective moves in the virtual nature are more prone to induce cybersickness (cf. Litleskare et al., 2020). The used material was recorded in a Finnish semi-open coniferous forest in the fall of 2022 during a partly sunny/cloudy weather (Fig. 2; SM.C.5). For the recording, Insta360 Pro2 8K 360-degree camera (Arashi Vision Inc, 2024a) was used together with an ambisonic sound recording system (RØDE, 2024; Zoom, 2024). Both video and sound were recorded simultaneously. Post-production was made by using Insta360Stitcher (Arashi Vision Inc, 2024b) and Adobe Premiere Pro 2023; Adobe, 2023)

Fig. 2. The forest landscape used in the experiment.

software for the video and Reaper software (Cockos Inc, 2024) for the sound. No edits were made to the video nor the soundtrack except for some airplane noise being removed from the soundtrack.

The choice of location for the recording was based on our expert evaluation and findings from previous field studies (e.g., Simkin, Ojala, & Tyrväinen, 2020, 2021) on what has been found to function as a restorative forest environment conducted with a similar sample (i.e., participants living in the same county and city). A suitable location was found approximately 20 km away from the laboratory. The video material used in the study represented typical aged spruce stand in Finland that can be claimed to be a familiar and nonthreatening landscape to the participants, which – according to the scanning for threats theory (Browning & Alvarez, 2020) – supports benefiting from virtual nature exposure (Browning et al., 2021). Before the experiment, the material was tested with the used technologies by the authors and few independent evaluators.

Based on the decibel measurements, the sound average was 47.0 dB (A) during the virtual nature room condition and 43.0 dB(A) during the TV condition. In the VR headset condition, the sounds were played directly from the headset, and thus no decibel measurement was possible. Nevertheless, the volume was adjusted to match those of virtual nature room and TV as closely as possible. The room temperature for all the conditions was set to 22C degrees.

2.4. Measures of the present study and data pre-processing

2.4.1. Psychological measures

Different psychological scales related to psychological state were used to measure the participants' self-reported restoration, subjective vitality, affective response, and current stress. The selected scales have been widely used in similar studies (e.g., Annerstedt et al., 2013; Mattila et al., 2020; Spano et al., 2023; Tyrväinen et al., 2014). The participants answered the scales before and after each experimental condition. The scales used in the present study are reported below.

The six-item Restoration Outcome Scale (ROS) (Korpela, Ylén, Tyrväinen, & Silvennoinen, 2008; cf. Hartig, Lindblom, & Ovefelt, 1998) was used to measure restoration. Four items out of the six original items in the Subjective Vitality Scale (SVS) (Bostic, McGartlandRubio, & Hood, 2000; Ryan & Frederick, 1997) were used to measure subjective vitality, that is, the positive feelings of aliveness and energy. The selection of four items was due to the synonymous nature of the scale items and the words available in the language in which the study was conducted. Similar operationalization has been used previously by Ojala, Korpela, Tyrväinen, Tiittanen, and Lanki (2019). The Positive and Negative Affect Schedule (PANAS) (Watson, Clark, & Tellegen, 1988) was used to measure positive and negative affect. The PANAS has two 10-item scales, one for positive affect (PANAS-Pos) and one for negative affect (PANAS-Neg). The current stress (stress-symptoms item (SSI)) was measured with a single-item question adapted from Elo, Leppänen, and Jahkola (2003) and was formed as follows: "Stress means a situation in which a person feels tense, restless, nervous or anxious or is unable to sleep at night because his/her mind is troubled all the time. Do you feel this kind of stress at the moment?".

The items of all the psychological measures are presented in SM.E.1. The ROS, SVS, PANAS, and SSI were all measured by using a Likert scale. The response options ranged from 1 (not at all) to 7 (completely) for ROS and SVS, from 1 (very slightly or not at all) to 5 (very much or completely) for PANAS, and from 1 (not at all) to 5 (very much) for SSI.

2.4.2. Covariates

Six variables were used as covariates in the present study: immersive tendency, technology innovativeness, nature relatedness, perceived stress, age, and gender. Immersive tendency was measured by 11 items from the Immersive Tendencies Questionnaire (ITQ) (Witmer & Singer, 1998). It is a trait-like personal feature that refers to the individual tendency to become immersed or involved in an attention-demanding task in an immersive virtual environment, which could potentially influence the effects of exposure to virtual environments (Witmer & Singer, 1998). The same applies for technology innovativeness, which was measured by the Personal Innovativeness in the Domain of Information Technology scale (PIIT) (Agarwal & Prasad, 1998). It refers to the individual perceptions about new information technologies and how they are accepted. As two of the used technologies (VR headset and virtual nature room) are rather novel, the individual perceptions about new information technology could potentially have some influence on the results (Fagan, Kilmon, & Pandey, 2012). An individual who is generally hesitant towards new technologies could be less receptive to virtual nature than an individual with a more welcoming approach towards new technologies (Knaust et al., 2021). Nature relatedness was measured by the 6-item version of the Nature Relatedness Scale (NR-6) (Nisbet & Zelenski, 2013). Nature relatedness, conceptualized as a trait, assesses the degree to which an individual relates themselves to nature in general. This can potentially influence the benefits received from nature exposure as suggested in prior research (cf. Pritchard, Richardson, Sheffield, & McEwan, 2020; Spano et al., 2023). Perceived stress was measured by the Perceived Stress Scale (PSS10) (Cohen & Williamson, 1988). It denotes the amount of general stress an individual has experienced over the past month. Logically, a highly stressed individual has higher potential to benefit more from a restorative nature experience than an individual with low perceived stress (Wolf, 2017). Gender and age are typical covariates in psychological studies and also the most typically controlled sociodemographic characteristics in virtual nature studies (Browning et al., 2021). Litleskare et al. (2020) also recommend using gender and age as covariates in virtual nature studies. The items of all the covariates are presented in SM.E.2.

2.5. Statistical analysis

The study design is a three-condition randomized trial with pre-post assessments and a crossover design, in which there were two measurements of each psychological variable within each visit: "before" exposure and "after" exposure. Study participants were randomized to six different condition order groups (123,132,213,231,312,321: 1. TV, 2. VR headset, 3. virtual nature room). Each study participant visited once in each condition. Instead of analyzing the original measurements, the change between timepoints (before−after) of each psychological variable was used as a response variable (Response change variable). This approach simplifies the design and the model to a three-condition, three-visit, six-condition order crossover study with a model structure:

Response change variable = Intercept + Visit(F) + Condition(F) + Condition order(F) + Gender(F) + Baseline covariate(F)(visit) + Covariates(F) + Visit day(R).

In the formula, F stands for fixed effect, and R for repeated random effect. The Baseline covariate is a visit-wise baseline measure for response variable at "before" and it is included due to design structure. Baseline covariate adjusts and normalizes the visit day variation of each participant. Covariates are continuous variables that were asked or measured before the study: immersive tendency, technology innovativeness, nature relatedness, perceived stress, and age. Visit day is a continuous variable, and it is used to model the covariance structure due to uneven time intervals between visits, with each study participant (identified by Person ID) as the individual unit/subject. Condition order -term estimates the carryover effect and in the case of $p < 0.05$ only the 1st visit data will be analyzed.

A general linear mixed model was fitted using normal distribution assumption (identity link) (Stroup, 2013). The model fit was checked from the shape of Pearson residuals and from the observed vs. predicted plots. The distribution of all response change variable values were symmetrical, and no transformation was applied to any of these variables.

The effect of statistical outliers (|Pearson residual|>2.5) were checked by removing these values from the data. The interpretation of the results did not change except with PANAS-Neg variable for which an additional analysis was conducted (SM.D.1; SM.D.2; see SM.D.9). In the model without any covariates, the interpretation of the results remained intact with the exception of ROS–TV, which was statistically significant only in the model without covariates. However, the direction was the same as in the model with covariates (SM.D.1; SM.D.3; see SM.D.9). Thus, the results of the original model with covariates were followed.

A Kenward-Roger approximation was used to analyze degrees of freedom. Statistical tests were based on predefined contrast comparisons according to study hypothesis, and simulation-based multiplicity-adjustment – to account for type 1 error – were used when applicable (Westfall, 1997).

Predefined statistical contrast comparisons according to study hypothesis:

a) H1 change in time, average over all conditions: |estimate| > 0 (1-sided *t*-test)
b) H1 change in time, condition wise: |estimate| > 0 (1-sided *t*-test)
c) H2a virtual nature room > control: |difference estimate| > 0 (1-sided *t*-test)
d) H2b VR headset > control: |difference estimate| > 0 (1-sided *t*-test)
e) H3 virtual nature room ≠ VR headset: difference estimate ≠ 0 (2-sided *t*-test)

All results presented are adjusted for gender and covariates. The modeling was performed by the GLIMMIX procedure of the SAS/STAT software (version 9.4, SAS Institute, 2020).

A detailed and extended description of statistical analyses, handling of covariates, power calculations, effect size calculations, and sample size calculations are given in SM.B.

3. Results

3.1. Covariates and carryover effect

No statistically significant effect of gender, age, ITQ, NR-6, and PIIT in the models was found (SM.D.4; SM.D.10). Perceived stress (PSS10) had a positive slope for ROS (0.035, 95% CI 0.013–0.057), which means that a 10-unit difference between two study participants in PSS10 measurement before the study affected 0.35-unit difference in response change variable ROS. Similarly, perceived stress (PSS10) had a positive slope for SVS (0.024, 95% CI 0.003–0.046), which means that a 10-unit difference between two study participants in PSS10 measurement before the study affected 0.24-unit difference in response change variable SVS (SM.D.4). In other words, a participant with large PSS10 value before the study got larger change in ROS and SVS between before/after virtual nature exposure measurements compared to a participant with small PSS10 value before the study.

In the case of PANAS-Pos, a statistically significant carryover effect was observed, that is, the previous condition effect is suspected to affect the next condition effect. Therefore, these effects are confounded at 2nd and 3rd visit and only 1st visit data is used (SM.D.4). As a statistically significant carryover effect was observed only in the case of PANAS-Pos, we consider that the one-week washout was sufficient in general.

The baseline covariate ("before" measurement) is a structural component of the study design and if it is working supposedly, it is statistically significant, which was the case for all the response variables (SM.D.4).

3.2. Differences between before and after the exposure

In terms of the main effect of Time (before−after), the participants' perceived restoration increased (ROS: 0.267, 90% CI -0.370 to -0.163), while current stress (SSI: 0.351, 90% CI 0.260–0.442) and negative affect decreased (PANAS-Neg: 0.230, 90% CI 0.198–0.261) during the exposure. When measuring the effect sizes by Cohen's *d* values, the effect size for PANAS-Neg was 1.531, indicating a very large effect; the effect size for ROS was −0.514, indicating a medium effect; and the

Table 2
Differences between before and after the exposure (before minus after) (Hypothesis 1).

Measure	Difference Estimate	*90% CI*	*t*	*df*	*p*	Cohen's *d*
PANAS-Neg	0.230	0.198–(0.261)	12.204	63.5	**<0.0001**	1.531
TV	0.192	0.150–(0.235)	7.522	141.4	**<0.0001**	0.632
VR headset	0.249	0.207–(0.292)	9.703	139.3	**<0.0001**	0.822
VN room	0.247	0.205–(0.289)	9.693	142.2	**<0.0001**	0.813
PANAS-Pos	0.045	(-0.064)–0.153	0.692	52.0	0.246	
TV	0.058	(-0.126)–0.242	0.527	52.0	0.300	
VR headset	0.173	(-0.015)–0.362	1.541	52.0	0.065	
VN room	-0.097	(-0.285)–0.091	-0.864	52.0	0.196	
ROS	-0.267	(-0.370)– -0.163	-4.303	70.0	**<0.0001**	-0.514
TV	-0.104	(-0.237)–0.028	-1.303	135.5	0.097	
VR headset	-0.317	(-0.451)– -0.184	-3.929	134.5	**<0.0001**	-0.339
VN room	-0.379	(-0.511)– -0.246	-4.743	135.3	**<0.0001**	-0.408
SSI	0.351	0.260–(0.442)	6.457	69.6	**<0.0001**	0.774
TV	0.236	0.112–(0.359)	3.155	146.7	**0.001**	0.260
VR headset	0.406	0.281–(0.530)	5.380	144.9	**<0.0001**	0.447
VN room	0.411	0.288–(0.535)	5.525	147.3	**<0.0001**	0.455
SVS	-0.070	(-0.164)–0.025	-1.229	63.8	0.111	
TV	0.104	(-0.028)–0.236	1.299	148.4	0.098	
VR headset	-0.112	(-0.245)–0.021	-1.389	146.5	0.084	
VN room	-0.201	(-0.333)– -0.069	-2.524	149.4	**0.006**	-0.206

Note. PANAS-Neg – Negative Affect; PANAS-Pos – Positive Affect; ROS – Restoration; SSI – Current stress; SVS – Subjective Vitality. VN room – Virtual nature room. Cohen's *d* for observed effect was calculated when $p < 0.05$. Due to 1-sided hypothesis, 90% CI are presented. Strictly, the upper or lower confidence limit does not exist due to direction of 1-sided hypothesis (within parenthesis). In all analyses, the difference estimate is the change between before and after the exposure.

Table 3
Differences between the conditions (condition A (change within visit) minus condition B (change within visit)) (Hypotheses H2a, H2b, H3).

Measure (H)	Estimate	*CI*	*t*	*df*	adjusted *p*	Cohen's *d*
PANAS-Neg						
1 vs 2 (H2b)	-0.057	(-0.120)–0.005	-1.894	133.0	0.072	
1 vs 3 (H2a)	-0.055	(-0.117)–0.008	-1.817	129.7	0.072	
2 vs 3 (H3)	0.003	-0.069–0.074	0.088	127.5	0.930	
PANAS-Pos						
1 vs 2 (H2b)	-0.115	-0.449–(0.218)	-0.725	52.0	0.236	
1 vs 3 (H2a)	0.155	-0.180–(0.490)	0.969	52.0	0.168	
2 vs 3 (H3)	0.270	-0.101–0.642	1.765	52.0	0.192	
ROS						
1 vs 2 (H2b)	0.213	0.029–(0.396)	2.400	135.2	**0.009**	0.206
1 vs 3 (H2a)	0.274	0.092–(0.457)	3.110	133.4	**0.003**	0.269
2 vs 3 (H3)	0.062	-0.146–0.269	0.701	130.1	0.485	
SSI						
1 vs 2 (H2b)	-0.170	(-0.354)–0.014	-1.900	137.1	0.061	
1 vs 3 (H2a)	-0.176	(-0.359)–0.007	-1.976	134.5	0.061	
2 vs 3 (H3)	-0.006	-0.218–0.206	-0.066	133.6	0.948	
SVS						
1 vs 2 (H2b)	0.216	0.012–(0.419)	2.199	133.0	**0.015**	0.191
1 vs 3 (H2a)	0.305	0.102–(0.508)	3.118	131.4	**0.003**	0.272
2 vs 3 (H3)	0.090	-0.140–0.320	0.918	128.3	0.361	

Note. PANAS-Neg – Negative Affect; PANAS-Pos – Positive Affect; ROS – Restoration; SSI – Current stress; SVS – Subjective Vitality. Condition: 1 – TV, 2 – VR headset, 3 – virtual nature room. Cohen's *d* for observed effect were calculated when $p < 0.05$. Strictly, due to 1-sided hypotheses (H2a and H2b), the upper or lower confidence limit does not exist (within parenthesis) and the value in the CI column represents 90% CI; H3 is a 2-sided hypothesis and the value in the CI column represents 95% CI.

effect size for SSI was 0.774, indicating a large effect (Cohen, 1988). For PANAS-Pos and SVS, no statistically significant differences were observed (Table 2; Fig. 3; SM.D.1). The condition-wise differences between before and after the exposure largely followed those of the pooled differences. Only exceptions were in ROS–TV (no statistically significant difference) and SVS–virtual nature room (SVS: 0.201, 90% CI

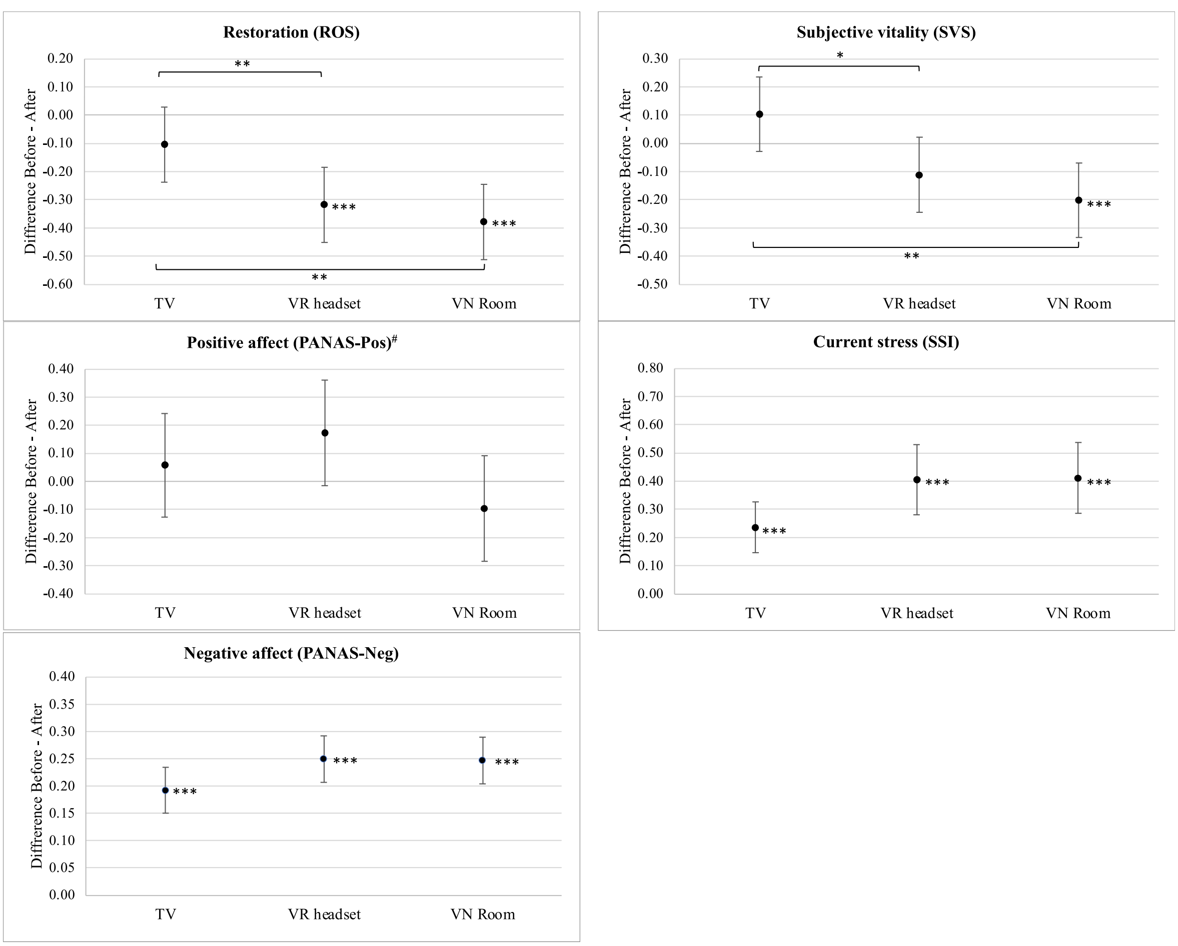

Fig. 3. This figure presents 1) the differences between before and after the exposure by virtual nature condition and 2) the differences between the conditions. 1) Dots and error bars describe the response change variable mean values (differences between before and after the exposure by condition) and their 90% confidence intervals. 2) The connection lines describe statistically significant differences between the conditions (condition A (change within visit) minus condition B (change within visit)). *Note.* ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$. #PANAS-Pos: Because of statistically significant carryover effect, only the 1st visit data was used.

-0.333 to -0.069). For details and all the condition-wise differences between before and after the exposure, see Table 2; Fig. 3.

3.3. Differences between the conditions

In terms of the main effect of condition (condition A (change within visit) minus condition B (change within visit)), the VR headset condition had a more restorative impact compared to the control condition (TV) (ROS: 0.213, 90% CI 0.029–0.396). Similarly, the virtual nature room condition had a more restorative impact compared to the control condition (TV) (ROS: 0.274, 90% CI 0.092–0.457). In both cases, the effect sizes measured by Cohen's *d* were small (0.206 and 0.269) (Cohen, 1988) (Table 3; Fig. 3).

In addition, subjective vitality increased more in the VR headset condition than in the control condition (TV) (SVS: 0.216, 90% CI 0.012–0.419). Similarly, subjective vitality increased more in the virtual nature room condition than in the control condition (TV) (SVS: 0.305, 90% CI 0.102–0.508). In both cases, the effect sizes measured by Cohen's *d* were small (0.191 and 0.272) (Cohen, 1988).

For PANAS-Neg, PANAS-Pos, and SSI, no statistically significant differences were observed between the conditions. Further, there was no statistically significant differences between the VR headset and virtual nature room conditions in any of the measures (Table 3; Fig. 3; SM.D.1).

For the model estimated mean changes in the psychological measures before the exposure and after the exposure as well as for the model estimated differences between conditions, see SM.D.1. For covariate estimates, fixed effect parameter estimates, and random effect parameter estimates, see SM.D.4. For model residual check and details, see SM.D.2, SM.D.5, and SM.D.9. For models without covariates and details, see SM.D.3, SM.D.6, and SM.D.9. For the descriptive statistics, including means and standard deviations of all the measures before and after the exposure, see SM.D.7, and for the correlations, see SM.D.8.

4. Discussion

4.1. Significance of the results

The accessibility and cost of different delivery technologies of virtual nature are still determining factors, making it essential to assess whether there are substantial differences between them regarding well-being outcomes. Comparing different technologies, having TV screen as a control technology, and using the same virtual nature material enables a genuine comparison of different technologies and makes the present study especially important in this research field.

Partly supporting H1, the participants' perceived restoration increased (except in the TV condition) while current stress and negative affect decreased during the exposure across conditions, with medium to very large effect sizes. However, for subjective vitality (except in the virtual nature room condition) and positive affect, no statistically significant differences were observed, meaning that in terms of these outcomes, H1 was not supported. For virtual nature room, the findings support the results of Takayama et al. (2022), who have conducted one of the few experiments with room-scale virtual nature, as they also found an increase in restoration and a decrease in negative affect after a virtual nature exposure. For VR headset, the findings complement previous literature presenting the potential of VR headsets in improving the psychological state (e.g., Browning, Mimnaugh, et al., 2020; Mattila et al., 2020).

Interestingly, virtual nature room was the only condition with a statistically significant increase in subjective vitality. Previously, virtual nature exposure with VR headset has been found to increase subjective vitality (Mattila et al., 2020). Hence, our findings on subjective vitality partly contradict those of Mattila et al. (2020). It is difficult to estimate where this difference arises, as there is a notable lack of studies concerning virtual nature and subjective vitality (Spano et al., 2023). The noteworthy difference between our study and Mattila et al. (2020) study was that their virtual nature environment was created using the Unreal game engine. Further, in the study by Ojala et al. (2022), virtual nature exposure with TV screen accompanied by nature sounds even decreased subjective vitality. Thus, the influence on subjective vitality might be highly context-dependent in the case of virtual nature. Spending time outdoors in nature typically enhances subjective vitality (e.g., Tyrväinen et al., 2014). In the present study, subjective vitality increased only in the virtual nature room condition, suggesting that this environment provided the closest experience to real nature. However, this finding requires further investigation. In terms of positive affect, no statistically significant differences were observed in any of the conditions. Previous findings on virtual nature and positive affect have been mixed even across systematic reviews. For example, Li et al. (2023) found an increase in positive affect resulting from virtual nature exposure, while Frost et al. (2022) did not. On the same line, Spano et al. (2023) showed that the evidence on virtual nature's influence on positive affect is inconsistent. It could be that virtual nature exposure leads to calming of emotional state, which can result in complex affective responses.

Overall, the present study demonstrates that a 15-min virtual nature exposure benefits psychological state. Furthermore, as no effects of ITQ, NR-6, or PIIT in the models was found, it indicates that the observed effects were not resulting from immersive tendency, nature relatedness, or technology enthusiasm. These findings provide further evidence of the potential for using virtual nature to enhance psychological state in places and situations where access to actual nature is limited. A 15-min exposure appears to be adequate time to induce positive effects. However, based on the present study, it is not possible to evaluate whether the effects would be significantly different after a longer (e.g., 60-min) exposure. Longer than 15-min visits to actual nature have been found to strengthen psychological outcomes such as restoration and creativity (e.g., Tyrväinen et al., 2014), and therefore, more research is needed to understand how longer virtual nature exposure may impact mental well-being and other outcomes. In practical terms, using virtual nature in workplaces, educational facilities, elderly care, or even private homes can be a feasible way to improve the indoor ambience and promote stress recovery.

In line with H2a and H2b, both the VR headset and the virtual nature room were found to be more effective settings than the control condition (TV) for psychological state. Restoration and subjective vitality increased more in both of these conditions compared to the control condition (TV). However, for positive affect, negative affect, and current stress, no statistically significant differences were observed between the conditions. Yet, also with positive affect, negative affect, and current stress—while not statistically significant differences—the model estimates mostly favor the VR headset and virtual nature room conditions over the control condition (TV). To our best knowledge, this is the first study to compare a room-scale virtual nature technology with a TV screen. Previous studies have compared screens with VR headsets using 360-degree videos, VR headset generally demonstrating better effects on psychological state (Knaust et al., 2022; Liszio et al., 2018). The present study demonstrates that VR headsets and virtual nature rooms are more effective delivery technologies for benefiting psychological state than a 75″ TV screen, although a virtual nature exposure via TV screen may also reduce negative affect and current stress. This difference is potentially a result of the immersion level of these technologies and the differences in the ability to look in multiple directions, which are likely to provide higher perceived presence (i.e., psychological sense of being in the virtual environment, Slater & Wilbur, 1997) (Baños et al., 2004; Cummings & Bailenson, 2015).

H3, on the other hand, did not receive support as there were no statistically significant differences between VR headset and virtual nature room conditions in any of the measured outcomes. However, while not statistically significant, the model estimates favor the virtual nature room condition over the VR headset condition in positive affect, restoration, subjective vitality, and current stress. Virtual nature room was also the only condition where there was a statistically significant increase in subjective vitality. This is partly in line with Li et al. (2023), who found in their review-based meta-regression that medium immersion level technologies (such as virtual nature rooms) produced a large effect on positive affect improvement, whereas high immersion level technologies (such as VR headsets) produced a small effect. Indeed, it seems plausible that medium immersion level technologies might be the most potential ones for benefiting psychological state, whereas low immersion level technologies seem the least potential. Though it needs to be noted that the classifications of technologies by their immersion level are often ambiguous and drawing the line between low, medium, and high is not always obvious.

To our best knowledge, this is the first study to compare a room-scale virtual nature technology with a VR headset. Previous research has suggested that, in general, virtual nature rooms might have specific benefits over VR headsets: Frost et al. (2022) note the potential value of virtual nature rooms over VR headsets in terms of lesser anxiety and cybersickness, and in terms of higher usability and feasibility. Hejtmánek, Hůla, Herrová, and Surový (2022) found that cybersickness may limit the potential effectiveness of virtual nature exposure. Thus, as the chances for cybersickness are likely smaller in virtual nature rooms than with VR headsets, virtual nature rooms would probably be better accepted by the users.

Virtual nature rooms also allow joint evaluations and simultaneous activities in a different manner than VR headsets do. While modern VR headset techniques already enable social interaction with others within the virtual environment, also across distances via the internet, the interaction with others in a virtual nature room has the benefit of enabling physical collaboration and seeing the gestures of others. One can also conduct activities, which wearing a headset would prevent. On the other hand, VR headsets have the advantage of not occupying a physical space. Then again, virtual nature rooms are easier to use in most cases, as one can just tap a touch screen to start presenting the material. Using VR headsets requires more technological savviness. Based on our own experience, creating virtual nature material is easier for VR headsets and it is also easy to find virtual nature material created specifically for VR headsets from the internet. Of course, for research purposes, we would recommend creating the virtual nature material by yourself to meet specific research needs. From the budget perspective, the cost of virtual nature rooms is still high compared to the current mainstream consumer VR headsets. VR headsets are also much easier to acquire. Though in most cases one virtual nature room would suffice, whereas several headsets might be required to meet the given demands. In general, VR headsets might offer a more cost-effective way for providing restorative virtual nature experiences than virtual nature rooms, but higher costs can be justified for larger user groups. Nevertheless, when choosing the delivery technology, factors like user group, use purpose, ease of use, individual preferences, quality, technology availability, and budget are also important to consider. Overall, choosing the most suitable delivery technology of virtual nature depends on the use purpose and the user group. Further research, however, is needed to identify which technologies are suitable and best accepted by different user groups for different restorative and other purposes. Nevertheless, the present study demonstrates that both VR headsets and virtual nature rooms are good options to benefit psychological state when access to actual nature is limited.

4.2. Limitations & future research

The present study has some potential limitations. First, due to the nature-related fields of some of the university faculties and national agencies operating in the campus area where participant recruitment was partly conducted, a bit over half (56.5%) of the sample consisted of participants whose current work or studies were somehow related to nature. This might have had some influence on the results in some way, although no statistically significant effect of nature relatedness (NR-6) in the models was found. The sample did also include participants from outside the campus area, and for almost half (43.5%) of the sample, their work or studies were not related to nature. Hence, the sample was rather balanced in this sense. Therefore, we see the risk of subject bias as very small in this case. The age distribution of the sample was also quite balanced (Table 1). However, the sample was female-dominant (67.7%) and participants with a university degree (83.9%) were over-represented, which places some restrictions on the generalizability.

Second, psychological state was not studied based on individual differences nor how well the forest landscape used in the study met individual expectations or preferences. People can have somewhat different landscape preferences due to personal background characteristics and previous nature experiences, which might influence the effects of a given (virtual) nature environment on a personal level (Meidenbauer et al., 2020). For example, Ojala et al. (2019) found that in actual nature environments, people's urban or nature orientedness modified the effect of environment on restoration. Also, preferred or favorite landscapes enhance psychological self-regulation (e.g., Korpela, 1992), which might also be the case in virtual settings. In the present study, the type of nature material was chosen based on our expert evaluation and the results of previous studies on forest preferences and restorative forest environments conducted with a similar sample (Simkin et al., 2020, 2021). Yet, future studies could benefit from such experimental approaches where the participants can choose the virtual nature environment themselves.

Third, the experimental design did not include stress-elicitation session before the exposure, which might potentially lead to higher heterogeneity of baseline measurements and heightened risks of ceiling/floor effect and carryover effect. To account for this, a Baseline covariate was used, which is a visit-wise baseline measure for response variable at "before" and adjusts the visit day variation of each participant. Further, carryover effect was accounted for in the analysis, and the perceived stress (PSS10) was controlled for in the models (see section 3.1.). We also examined the data for ceiling/floor effects, which are a problem if more than 15–20% of the responses equal either the highest or lowest possible score (Garin, 2014). We noted a floor effect with SSI (20.4% of the responses were 1), however, while this most probably decreased the difference estimate, it did not affect the interpretation. On the other hand, not using a stress-elicitation session also better resembles a real-world situation: people do not go through specific stress-elicitation sessions but would use virtual nature during their day (with the current stress they have) similar to the participants in the present study.

The present study followed a purely quantitative approach, hence, the qualitative aspects of the virtual nature experience were left unexplored. Future studies should investigate also the qualitative aspects of different virtual nature environments and their delivery modes. The sensory stimuli used in the present study included visual and auditory. While these two are probably the most essential senses in delivering nature experiences and feasible ones to implement across different settings, future research could explore the potential additional benefits (or detriments) of using olfactory stimuli. In our experimental plan, no follow-up measures were conducted after the visits, and thus, it is not possible to assess how long the observed effects lasted. Investigating the dose-response and long-term effects of spending time in virtual nature would be a promising avenue for future research. Finally, the present study was conducted in springtime. A study by Litleskare and Calogiuri (2023) suggests that virtual nature might be more effective during autumn/wintertime compared to spring/summertime. Hence, it would be interesting to repeat a similar study during autumn/wintertime to see if it would bring additional benefits over springtime. Similarly, conducting a similar study in a region with very different climate, for example Southeast Asia, where the summers are very hot and humid, could create a greater discrepancy between real and virtual nature experiences and yield interesting findings.

CRediT authorship contribution statement

Tuomas Kari: Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Ann Ojala:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Conceptualization. **Mika Kurkilahti:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Liisa Tyrväinen:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

Ethical statement

All procedures were performed in compliance with relevant laws and institutional guidelines and have been approved by the appropriate institutional committee. The study was conducted in accordance with the principles of the Declaration of Helsinki. The ethical review statement for the present study was given by the Ethics Committee for Human Sciences at the University of Turku (#52/2022, 16.11.2022). Informed consent was obtained for experimentation with human subjects. The privacy rights of human subjects were always observed.

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Declaration of competing interest

None.

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Appendix A. Supplementary materials (SM)

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2024.102452.

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