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The impact of visualization techniques of immersive virtual scenarios in promoting nature connectedness: A blind randomized controlled trial with mixed-methods approach

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ABSTRACT

Background: Little is known on whether and how different visualization techniques used to develop Immersive Virtual Nature (IVN) scenarios influence the users' subjective experience and feelings of nature connectedness.
Methods: Sixty healthy adults were randomly allocated to walk for 10 min on a treadmill whilst facing a blank wall (control) or being exposed to one of two IVNs (a 360° video or a matching computer-generated scenario) with equal levels of interactivity. The state version of the Connectedness to Nature Scale (CNS) was administered before and after each experimental condition. Moreover, in-depth follow-up interviews were conducted among five participants to investigate their experiences and perceptions during the IVN experience.
Results: Both IVN scenarios elicited a statistically significant increase in CNS, with no differences between the two scenarios. No statistically significant increase was found in the control condition. From the qualitative analysis, four overarching themes were identified (IVN as present and distinct experience, Impact of technical equipment, Qualities of the IVN landscape, and Affective and physical responses), depicting the facilitators and barriers influencing the IVN experience.
Conclusion: With equal levels of immersion and interaction, 360° videos and computer-generated IVNs can be equally effective in eliciting increased feelings of nature connectedness. The IVN experience was generally perceived as a distinct experience, not merely a (poor) simulation of actual nature-interactions. However, characteristics of the technology or the virtual environment can influence the overall experience. These findings provide novel insights and further understanding of IVN as a tool in the promotion of nature connectedness.

1. Introduction

1.1. Nature connectedness

Nature connectedness, a perceived connection to the natural world (Mayer & Frantz, 2004), has been consistently associated with pro-environmental behaviours (Mackay & Schmitt, 2019; Whitburn et al., 2020). Evidence exists supporting a *causal* link between the two variables, with interventions that successfully increased nature connectedness also leading to greater engagement in pro-environmental behaviours (Mackay & Schmitt, 2019). Studies also showed significant associations of nature connectedness with a variety of health and well-being outcomes, including overall happiness (Capaldi et al., 2014), positive affect (Mayer et al., 2009), vitality, and life satisfaction (Pritchard et al., 2020). Also in this case, evidence supports a causal link, as studies demonstrated that increased nature connectedness mediated and explained, at least in part, the enhanced psychological states and subjective wellbeing induced by contact with nature (Mayer et al., 2009; McEwan et al., 2019). Moreover, individuals with more positive feeling about nature are more likely to perform nature-based physical activity in amounts and intensity sufficient to elicit significant health benefits (Calogiuri, 2016; Calogiuri & Chroni, 2014). Considering these benefits,

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it is pertinent to address the question of how we can effectively foster people's nature connectedness. In this regard, studies consistently show that, while time spent in nature during childhood is a key predictor of people's nature connectedness in adulthood (Calogiuri, 2016; Rosa et al., 2018; Soga et al., 2020; Thompson et al., 2008), even brief experiences in nature can increase nature connectedness in adults (Sheffield et al., 2022).

1.2. Immersive virtual nature technology and visualization techniques

While limited or decreasing access to natural outdoor environments has become a global public health concern (Bratman et al., 2019; Larson et al., 2019), digital technologies have been affecting humans' encounters with the natural world (Frumkin et al., 2017; Murphy et al., 2022). In particular, in recent times, virtual reality (VR) technology has emerged as a promising tool to promote highly realistic and immersive experiences of nature to individuals who, for different reasons, cannot visit actual natural environments (Litleskare et al., 2020; White et al., 2018). VR is defined as "A medium composed of interactive computer simulation that senses the participant's position and actions and replaces or augments the feedback to one or more senses, giving the feeling of being mentally immersed or present in the simulation (a virtual world)" (Sherman & Craig, 2019, p. 13). Head-mounted displays (HMDs) that provide a 360° vision of the virtual world by sensing and matching the movements of the user's head while at the same time obstructing the vision of the actual surrounding premises, and that can be combined with different types of sensors that allow control of movement and navigation in the virtual environment, have in recent years emerged as a mainstream technology to deliver highly immersive VR experiences. Litleskare et al. (2020) introduced the concept of *immersive virtual nature* (IVN), referring to immersive VR technologies that specifically provide the illusory perception of being enclosed within and interact with a natural environment. Although IVN technology is incapable of delivering the full and complex sensory input that characterizes nature experiences (weather, smells, high levels of biodiversity, etc.), it can produce more realistic and effective experiences of nature compared with less immersive devices such as two-dimensional screens (Liszio et al., 2018; Yeo et al., 2020), and even provide psychological benefits somewhat similar to those experienced in actual natural environments (Browning et al., 2020).

Currently, two main visualization techniques are used to design IVN scenarios: 360° videos and computer-generated scenarios (Calogiuri et al., 2021, pp. 127–146). 360° videos are created by filming an actual environment using 360° cameras, and generally allow for highly realistic photographic representations of actual physical environments. These videos, however, are often limited to poor camera stabilization and low video resolution, factors that have been associated with negative user's experiences, including a higher risk of cybersickness (Saredakis et al., 2020). Furthermore, 360° videos generally offer little or no possibility to interact with the virtual world, as one can only view the predetermined sequence of images filmed, possibly only regulating the playback speed through controllers or cadence sensors. Another way to create IVN involves computer graphics, generated using video game techniques and three-dimensional (3D) modelling to digitally recreate representations of fictional or actual environments. Such computer generated IVNs can, potentially, offer greater level of interactivity, while on the other hand they may appear artificial or fictional. Both these aspects, however, are largely dependent on the complexity of the specific scenario as well as the abilities of the programmers who develop them.

1.3. Impact of visualization techniques on the User's experience

To the best of the authors' knowledge, only three studies (Litleskare et al., 2022; Nukarinen et al., 2020; Yeo et al., 2020) compared the way in which matching IVNs developed either as 360° videos or computer-generated scenarios influences the users' experience and psychophysiological responses. Nukarinen et al. (2020) compared a view on an actual outdoor forest environment with a 360° video and a matching 3D model, both reproducing the same location. They found no statistically significant differences in the way the 360° video or the 3D model influenced the participants' affect state. However, while no statistically significant differences were found between the actual forest and the 3D model, the participants reported a larger reduction of negative affect when exposed to the actual forest compared to the 360° video. Litleskare et al. (2022) compared a 360° video and a 3D model reproducing the same naturalistic location (a walking trail along a river), which were connected to a manually driven treadmill. The 3D model was associated with significantly higher levels of enjoyment compared with a control condition (walking on the treadmill whilst facing a white wall), while this effect was not replicated in the 360° video condition. On the other hand, no statistically significant differences were found among conditions in relation to the participants affect state. Yeo et al. (2020) investigated the effects of viewing a an underwater coral reef landscape delivered through a computer screen, a 360° video, or a computer-generated IVN on a variety of psychological outcomes. The findings indicate that the computer generated IVN, but not the 360° video, led to a significant increase in positive affect compared to the matching scenario displayed on the TV screen. However, the authors acknowledged that this finding might be influenced by the fact that the computer-generated scenario provided additional interactive feature (i.e., the possibility to explore the virtual world through hand-held controllers), which were not provided by the 360° video. Overall, these studies suggest that IVN developed as 360° videos, computer-generated IVNs may elicit more positive users' experiences and psychological responses, although these effects may be associated with the greater levels of interactivity that computer-generated scenarios often offer.

1.4. The effect of IVN on nature connectedness

Sneed et al. (2021) examined the effects of being in an actual natural environment (a trail in a wooded area along a pond) on the nature connectedness of university students, comparing it with exposure to a 360° video reproducing the same location and a 360° video reproducing the inside of a library. They found that the levels of nature connectedness increased significantly after both the actual and the IVN-mediated nature experiences, thought with a larger effect size for the experience in actual nature. However, when comparing the two 360° videos with each other, a statistically significant difference was not achieved. This finding is in contrast with other studies that compared IVNs with virtual urban landscapes, either developed as 360° videos (Leung et al., 2022) or computer-generated scenarios (Chan et al., 2021), and which found significantly larger increases in nature connectedness in favour of the IVN exposure. Yeo et al. (2020) compared the impact of different visualization techniques (i.e., a 360° video vs. a computer-generated scenario) on the extent to which IVN could elicit increased nature connectedness, founding a marginally significant larger effect in favour of the computer generated IVN (Yeo et al., 2020). However, as explained above, it is unclear whether this finding may be explained by the greater interactivity provided by the computer-generated IVN compared with the 360° video.

1.5. The present study

The research on the effects of IVN on nature connectedness is still at its infancy. While the few existing studies appear to support the assumption that IVN can induce acute changes in state nature connectedness, the evidence is still mixed and limited by poor control of possible confounders. In particular, the impact of different visualization techniques (360° videos vs. computer generated IVNs) on the extent to which IVN can elicit increased nature connectedness outcomes are largely unknown. Only one study have directly compared IVNs generated through these two distinct visualization techniques (Yeo et al., 2020), which were also associated with different levels of interactivity. To what extent the differences between the two types of IVN were associated with the specific visualization technique or the levels of interactivity remains, therefore, yet to be clarified. Moreover, there is a lack of studies qualitatively exploring the participants' perceptions of and experiences with different IVNs, which may provide further insights into the pathways linking IVN exposure to nature connectedness. To address this gap, using a mixed methods approach, we investigated possible changes in state levels of nature connectedness in healthy adults after a 10 min' simulated nature walk, comparing a 360° video with a matching computer-generate 3D model with equal levels of interactivity. Furthermore, in a sub-group of participants, we conducted in-depth interviews to explore their perceptions and experiences. The following research questions were outlined.

RQ1) Does a 10 min' IVN exposure simulating a nature walk lead to acute changes in nature connectedness, compared to control (i.e., walking on a treadmill with no exposure to IVN), among healthy adults?

RQ2) Do possible changes in nature connectedness elicited by a 10 min' IVN exposure simulating a nature walk differ depending on the visualization technique (i.e., a 360° video vs. a computer-generated 3D model reprocucing the same location shown in the video)?

RQ3) What are the perceived facilitators and barriers that influence the IVN experience, which may support or hinder enhanced feelings of nature connectedness, among the participants?

2. Materials and methods

2.1. Study design

This study is part of a larger project, which was prospectively registered (trial ID: ISRCTN14275608). Additional findings collected in the context of this project, which relate to the psychophysiological benefits associated with exposure to IVN and their potential for the promotion of nature-based physical activity, have been reported in separate publications (Calogiuri et al., 2022; Litleskare et al., 2022), according with the registered publication plan. The present paper is structured in line with the CONSORT guidelines (Altman, 2001).

2.1.1. The experimental trial

A double-blind parallel randomized controlled trial was conducted at the Sport Physiology Laboratory of Inland Norway University of Applied Sciences – Campus Elverum, which is equipped with a standardized temperature (18 °C), ventilation, lighting, and a high degree of sound insulation. The participants were randomly assigned to one of three conditions: 1) 360° video, 2) computer-generated IVN (3D model), or 3) control group (blank wall). A parallel groups design was deemed as most appropriate, rather than a cross-over design, to reduce the potential impact of carry-over and expectancy effects (Litleskare et al., 2020). The participants were blinded to the allocated condition to avoid an expectancy effect (i.e., they were not informed to which condition they were allocated, nor were they made aware of what the other experimental conditions were). As the randomization (pick from a hat) was performed after the baseline assessment, the examiner was blinded to the allocation at baseline, though they were aware of the participants' allocated condition during the post-exposure assessment. The CONSORT flow diagram for the study is presented in Fig. 1.

2.1.2. Mixed methods approach

The present study adopted a convergent mixed method design in line with the framework provided by Fetters et al. (2013) and Moseholm and Fetters (2017). At the methods levels, the quantitative and qualitative strands were linked through sampling (connecting approach), with quantitative assessments performed shortly before and after each experimental conditions and qualitative follow-up interviews conducted on a subset of the sample approximately one or two weeks after the exposure. Merging was performed, after independently completing the analysis of the quantitative and qualitative data (separative relation dimension), using an explanatory unidirectional approach, which is when "a quantitatively structured analysis is complemented by the qualitative data to provide a more comprehensive understanding of the phenomena of interest" (Moseholm & Fetters, 2017, p. 6). The merging was equivalently driven, with the researchers attempting "to listen to qualitative- and quantitative-related epistemologies or insights to produce a superior whole" (Moseholm & Fetters, 2017, p. 5). At the

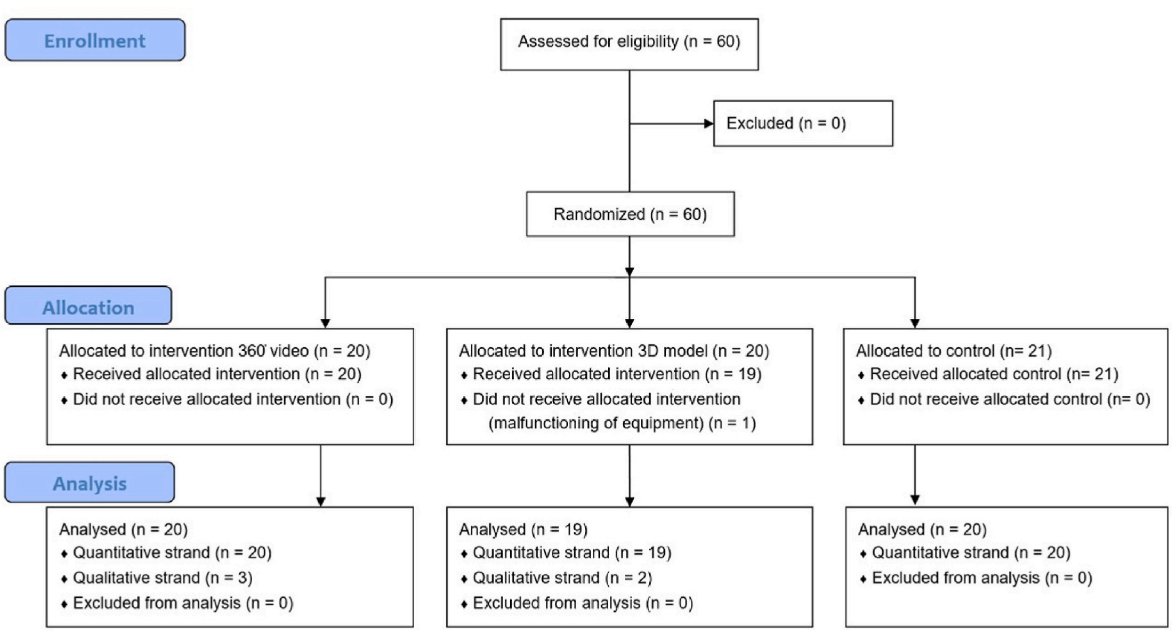

Fig. 1. CONSORT flow diagram of the progress through the phases (enrolment, intervention allocation, and data analysis) of the parallel randomised trial (Altman, 2001).

interpretation and reporting level, integration was done narratively, first presenting the findings of the quantitatively and qualitative strands in separate sections of the Results chapter (contiguous approach) and then discussing both qualitative and quantitative findings together on a theme-by-theme basis in the Discussions chapter (weaving approach). Emphasis was given on how the qualitative findings could expand on the quantitative findings.

2.2. Participants

For the quantitative strand, a sample size estimation was performed in G*Power, setting an Alpha of 0.05, a Power of 90%, and an expected medium effect size (f = 0.25), in line with previous literature (Sheffield et al., 2022; Yeo et al., 2020). This produced an optimal sample size of 54 participants. The final sample included 60 participants to account for possible missing data or extreme outliers (360° video: Males/females [n] = 12/8, Age [M ± SD] = 31.2 ± 13.7 years; 3D model: Males/females = 9/10, Age = 31.6 ± 15.3 years; Control: Males/females = 11/10, Age = 27.1 ± 7.3 years). The participants were recruited through announcements on the University's official web page, word of mouth, and social media. Inclusion criteria were being 18 years or older, having normal or corrected to normal sight, and reporting no diagnosed balance impairments. All participants were compensated with a 100 NOK (approximately 10 €) gift card. Most participants had tried VR before but were not regular users. For the qualitative strand, participants who had been assigned to one of the IVN conditions were invited to participate in a follow-up interview to share their thoughts and perceptions regarding their IVN experiences. In total, five participants (four females and one male, aged 20–63 years) accepted to undergo an interview, of whom three underwent the 360° video condition and two underwent the 3D model condition. Four of the participants were university students, and one was a university employee. Participation in the interviews was compensated with an additional 100 NOK gift card.

The study was conducted in compliance with the Declaration of Helsinki and the Guidelines for Research Ethics in the Social Sciences and the Humanities (National Research Ethics Committees, 2022). Approvals were obtained from the Regional Committees for Medical Research Ethics South-East Norway (ref. number 134663) and, for the qualitative part, the Norwegian Centre for Research Data (ID: 276667). All participants gave their written consent to participate in the study after being informed about the study's purpose and associated benefits and risks.

2.3. IVN technology in the experimental conditions

In all three conditions, the participants walked for 10 min on a manually driven treadmill (Woodway curve, Woodway inc., USA), while wearing the HMD or facing the blank wall. All participants were instructed to walk at a comfortable pace while holding on to the treadmill's handrails to maintain balance. The manual treadmill allowed participants to walk at a self-selected speed to increase ecological validity and facilitate pleasant experiences (Ekkekakis et al., 2011). The exposure duration of 10 min was chosen to comply with the minimum time to elicit positive psychological outcomes of real green exercise (Meredith et al., 2020). The walking speed in both IVN conditions was matched with the treadmill's speed by using a USB output connected to the treadmill. The playback was made via an HTC Vive Pro HMD (resolution of 2880 × 1600; refresh rate of 90 Hz) connected to a computer (Intel(R) i7-8700k processor, 16 gigabytes of RAM, NVIDIA Geforce RTX 2080 graphics card). Sony WH-1000X M3 noise-cancelling headphones (Sony Corporation, Tokyo, Japan) were used for the playback of the soundscape.

The two IVN conditions displayed the same scenery, a walk in an urban green space along a paved path by the river Glomma in Elverum (Norway). The virtual scenario was developed in a way that provided a first-person perspective on the surrounding environment. A previous study showed that a 10 min' walk in the actual location, during the same season and with similar weather conditions as those shown in the IVN, could elicit positive emotional responses among healthy adults (Calogiuri et al., 2018). The 360° video was developed using a GoPro Fusion 360° camera with a built-in stabilizer (5228 × 2624, resolution, 30 frames per second; GoPro, San Mateo, California, USA). The 3D model was based on 3D reconstruction techniques and was created with Unreal Engine 4.22 (Epic Games, Cary, North Carolina, USA). Detailed information about the technology is provided in Litleskare et al. (2022), while a demo of the two IVNs can be viewed through these links: https://www.youtube.com/watch?v=hK3vzKaHDao&t=1s and https://www.youtube.com/watch?v=8VKzMnU9Tno.

2.4. Procedures and data collection

2.4.1. Quantitative assessment of state nature connectedness

Possible changes in nature connectedness were assessed with the state version of the Connectedness with Nature Scale (CNS; Mayer et al., 2009) before (baseline) and after (post) exposure to each experimental condition. The instrument measures the extent to which one feels connected to the natural world at a given point in time, and it is sensitive to acute changes induced by contact with nature. It contains 13 items, for example, "Right now I'm feeling a sense of oneness with the natural world around me" and "Presently, I feel like I am part of the web of life". Each item is rated on a 5-point rating scale with anchors at 1 ("Strongly disagree") and 5 ("Strongly agree"). The scale's internal consistency was acceptable at both assessment time-points (α = 0.805 and 0.825, respectively).

2.4.2. Follow-up interviews

In the follow-up interviews, participants were asked to share their thoughts and perceptions regarding the VR experience. A semi-structured interview guide helped explore context-driven topics while leaving room for new themes to surface. Since the in-depth interviews were conducted during the Covid-19 pandemic, these were adjusted to the participants' preferences, resulting in three face-to-face interviews and two online interviews, which took place one to two weeks after the experiment in the lab. Each interview lasted between 30 and 45 min and was conducted by the same author (AH) in the participants' native language (Norwegian). Fig. 2 summarizes the overall study design and procedures.

2.5. Data analysis

2.5.1. Statistical analysis

Data were first explored for normal distribution and possible outliers and missing data. No missing or extreme values were identified, and CNS showed acceptable normal distribution at both assessments' points, as based on Shapiro Wilk test ($p > 0.05$ for both time-points), examination of frequency histograms, and values for skewness (−0.43 and −0.40 for the pre- and post-exposure assessment, respectively) and kurtosis (1.59 and 0.92 for the pre- and post-exposure assessment, respectively). Chi-squared test for independence or Student's t-tests for unrelated samples were performed to explore possible differences of age, gender, weekly physical activity levels, and CNS at pre-exposure among the participants who were allocated to the three experimental conditions, showing no significant differences among the groups. Descriptive statistics for CNS were computed and presented as means and standard deviations (M ± SD). To address RQ 1 and 2, a mixed between-within subjects' analysis of variance (ANOVA) with post-hoc analysis was performed, with "time" (pre- or post-exposure assessment) being set as within-subjects, while the between-subjects factor was "experimental condition" (360° video, 3D model, or control). Assuming that a statistical significance was achieved for the main or interaction effects, a post-hoc analysis applying Bonferroni's correction of alpha was conducted. Specifically, paired Student's t-tests were used to investigate possible

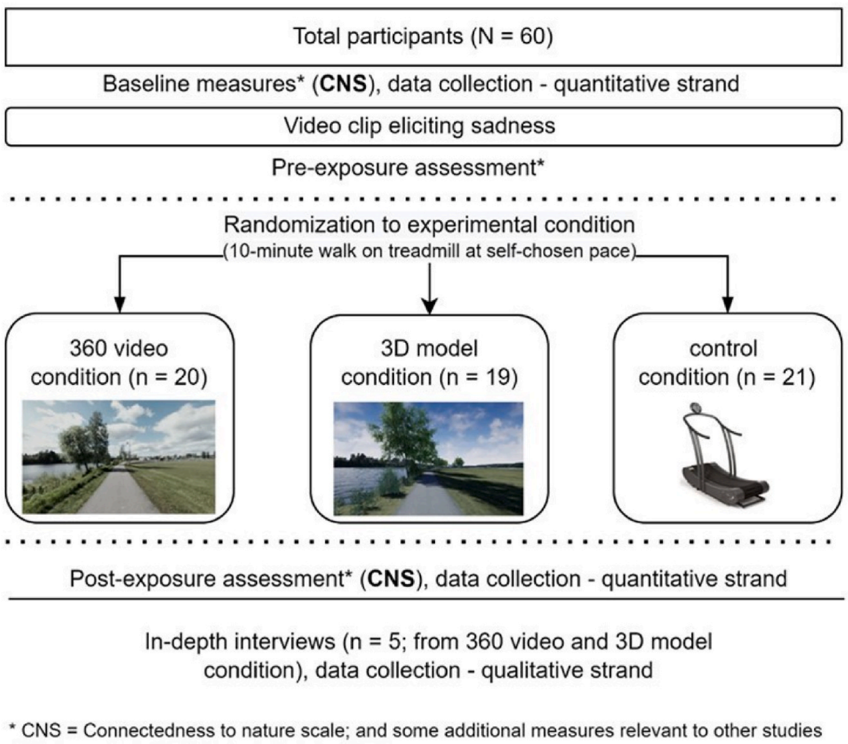

Fig. 2. Overview of the overall study design and the experimental procedures.
Note. Additional measurements regarding physio-psychological parameters (affect state, heart rate, and blood pressure) were collected and published in other papers (Calogiuri et al., 2022; Litleskare et al., 2022) and the RCT registry (trial ID: ISRCTN14275608). In line with a classic experimental paradigm (Steg et al., 2012), participants viewed a 2′50″ film clip that elicited sadness (Rottenberg et al., 2007) to reduce individual variations in these measurements. The baseline measurement of CNS was conducted before the elicitation of sadness and, as reported in Litleskare et al. (2022), the participants' affect profile returned to baseline levels after each experimental condition, with no difference among conditions. It is, therefore, reasonable to assume that the CNS measurements presented in the present study were not affected by the elicitation of sadness.

pre-to-post changes of CNS within each experimental condition, while Student's t-test for unrelated samples were used to establish whether there were statistically significant differences of CNS across groups. To account for individual differences at baseline and better capture the magnitude of the change, for the latter, delta values (pre – post) were used as dependent variable. Partial eta squared (η^2) and Cohen's d were

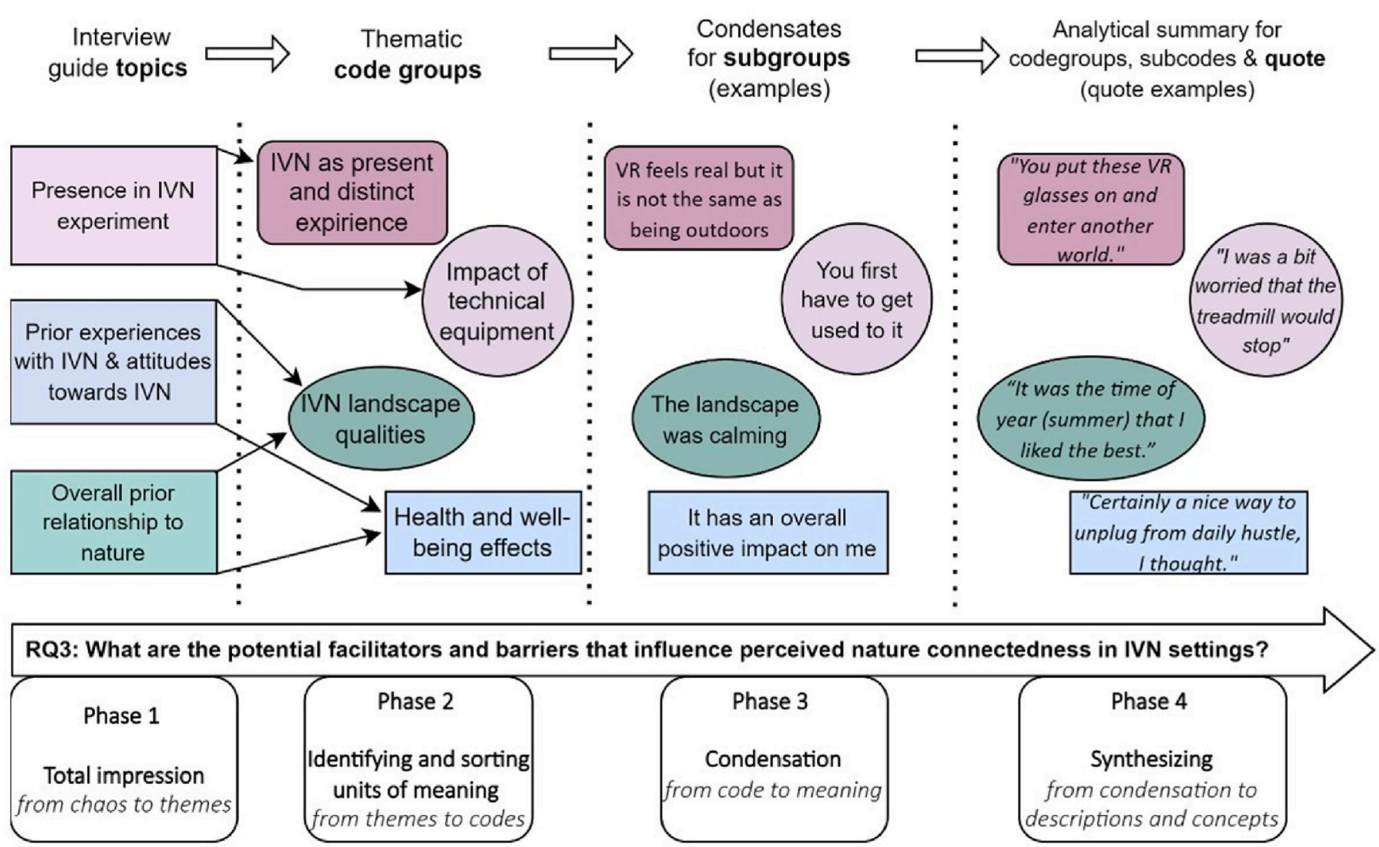

Fig. 3. The analytical process using Systematic Text Condensation, adopted from Malterud (2012) (Malterud, 2012).

computed to quantify the effect size for the ANOVA and the Student's t-tests, respectively. The level of significance was set at $p < 0.05$. The statistical analyses were executed in SPSS version 25 (IBM corp., New York, USA) by a senior researcher (GC).

2.5.2. Qualitative data analysis

The interview data were analysed through systematic text condensation (Malterud, 2012). The analysis procedure was executed in MAXQDA (version 20.4.0), an established software for qualitative data analysis. Fig. 3 provides a visual overview of the analytical process. As a first step of the analysis, two authors (EP and AH) read all the transcripts (59 text pages) separately to obtain an overall impression of the data. The identified preliminary themes associated with the research questions were then discussed to reach a consensus on the preliminary themes that should be further analysed. The initial interview questions were centred around three major topics: 1) feelings of presence in IVN, 2) previous experiences with and expectations toward IVN, and 3) the participants' overall relationship with nature. As a second step, the transcripts were systematically reviewed and coded line by line to identify text fragments (units of meaning) that contained information related to RQ3. In this abductive phase, new themes were generated while others were removed or merged as the data were analysed in detail. The data were reduced to a selection of meaningful units sorted into four thematic code groups: 1) IVN as present and distinct experience, 2) Impact of technical equipment, 3) Qualities of the IVN landscape, 4) Affective and physical responses. As a third step, code groups were treated as analytical units. The meaning units within the code groups were systematically sorted into subgroups. By reviewing and condensing the subgroups into artificial quotations, a condensate was created for each subgroup, adhering closely to the participants' wording. Illustrative quotations were identified for each of the final two to three subgroups. In the fourth and final step, generalized descriptions of the participants' experiences with and thoughts about the IVN situation were developed (analytical summary) and exemplified with a representative quotation from the interview transcripts. Before finishing the result report, transcripts were read once more to ensure that no content relevant to the study had been overlooked during the analytical process.

3. Results

3.1. Quantitative findings

Descriptive statistics for CNS at pre- and post-exposure for the three experimental conditions are presented in Table 1. The ANOVA showed a significant effect of time for all conditions combined ($F(1,57) = 8.119$; $p = 0.006$; $\eta^2 = 0.125$), as well as a significant time by condition interaction ($F(2,57) = 10.668$; $p < 0.001$; $\eta^2 = 0.273$). The post-hoc analysis comparing CNS in pre vs. post within each experimental condition found statistically significant increases for the 360° video ($t(19) = -3.153$; $p = 0.015$; $d = -0.705$) and the 3D model ($t(18) = -4.297$; $p = 0.003$; $d = -986$), but not for the control condition ($t(20) = 1.777$; $p = 0.273$; $d = 0.388$). The post-hoc analysis comparing CNS, expressed as delta values, across conditions found significantly larger increments of CNS for both the 360° video ($t(39) = 3.30$; $p = 0.004$; $d = 1.03$) and the 3D model ($t(38) = 4.13$; $p < 0.001$; $d = 1.31$) as compared with the control condition, with no statistically significant differences between the 360° video vs. the 3D model ($t(37) = -1.18$; $p = 0.860$; $d = 0.38$).

Table 1
Ratings of Connectedness to Nature Scale, state version (Mayer et al., 2009), measured before and after undergoing one of three experimental conditions and expressed as changes-from-baseline (M±SD).

Time-point	360° video (n = 20)	3D model (n = 19)	Control (n = 21)
Pre	3.23 ± 0.71	3.38 ± 0.55	3.23 ± 0.62
Post	3.40 ± 0.77*	3.65 ± 0.48*[a]	3.11 ± 0.68[b]
Delta (post – pre)	0.17 ± 0.24[a]	0.27 ± 0.27[a]	−0.13 ± 0.33[b,c]

*p < 0.05 (applying Bonferroni's correction of alpha) in the post-hoc comparison with "Pre".
[a] p < 0.05 (applying Bonferroni's correction of alpha) in the post-hoc comparison with "Control".
[b] p < 0.05 (applying Bonferroni's correction of alpha) in the post-hoc comparison with "3D model".
[c] p < 0.05 (applying Bonferroni's correction of alpha) in the post-hoc comparison with "360° video".

3.2. Qualitative findings

The extracted code groups, subcodes, and illustrative quotations can be found in Table 2. Based on the interview data, the potential facilitators and barriers that may influence the participants' perceived nature connectedness in the IVN setting are presented as four overarching themes.

3.2.1. IVN as present and distinct experience

All five participants experienced the IVN as highly realistic and immersive, with participants expressing feelings of presence in the virtual and detachment from the external, physical environment. While four participants mentioned time perception being altered, lack of a more holistic sensory experience (e.g., providing haptic or smell sensory information) was mentioned by two participants to clearly differentiate IVN from actual nature experiences.

3.2.2. Impact of technical equipment

All five participants described high levels of immersion in the IVN, but a sense of presence happened to be interrupted by the sudden awareness of the equipment, which delivered the illusory experience (e.g., fear of falling from the treadmill). Further, limitations of the IVN technology were especially evaluated as barriers to the illusory experience, directed towards the potential of improving the cohesiveness between the different technical equipment (treadmill and HMD).

3.2.3. Qualities of the virtual landscape

The qualities of the virtual environment showed to influence the overall IVN experience. Relevant landscape features were the familiarity with the original actual landscape, the displayed season of the year, perceived (bio)diversity, and the degree of perceived wildness. Participants had in common that they were well familiar with the actual landscape, which was mostly evaluated positively. Three participants expressed appreciation for recognizing natural elements and environmental features such as the leaves waving in the wind, the view of water, and in particular the bright light and summer weather. Within their reflections around comparison to the original actual landscape, three of the participants expressed a wish for more (bio)diversity and four participants stated that they would have enjoyed a higher degree of perceived wilderness in the IVN scenario, for instance, a forest or mountain landscape.

3.2.4. Affective and physical responses

All participants described the overall experience as fascinating and mentally restorative. Especially, the bright light, summer season, and river landscapes were frequently mentioned as providing an energizing effect. The IVN landscapes also evoked pleasant memories of previous experiences of original or similar actual landscapes among three of the participants. Both the 360° video and 3D model provided a distraction from the physical exertion and, with time seemingly passing faster than expected, three participants only realizing after the experiment that they were tired from walking. Negative emotional responses were also reported. For instance, one participant reported a moment of feeling of panic, related to experiencing strong presence in the IVN. The overall positive evaluation of the IVN experiences brought some participants to

Table 2

Representative quotes from the follow-up interviews, categorized by theme.

Codes and subcodes	Illustrating quotes	
	Facilitators	Barriers
1. IVN as present and distinct experience 1.1. Sense of reality[a] 1.2. Perceived difference to real nature[b]	“I noticed the effect when I took off the glasses. It was like this: ‘Wow, it was like a world of its own and I was present in it’.” *Female, 21 years, 3D model* “I didn’t imagine that I would be so involved in the experience, that it would feel so realistic. After 5 min had passed, I kind of wanted to be there for an hour.” *Female, 63 years, 360° video* “I had no idea how long I had walked for (…) in the real world, I normally am quite good at estimating time.” *Male, 29 years, 360° video*	"It [the IVN] might not be quite as clear as usual. And when you go in the real world, cars come and you meet people (…) You have sound here [in the IVN] and things like that, but you don’t feel the air … but I thought it was certainly a nice way, to disconnect from everyday thoughts for a little while." *Female, 21 years, 3D model*
2. Impact of technical equipment 2.1. Level of immersion[a] 2.2. Coherence and compatibility of equipment[b]	“Compared to the VR experience I had four years ago, I thought this was very real, (…) I was surprised that the light did not even seem like computer screen light.” *Male, 29 years, 360° video*	“It was perhaps a bit distracting compared to just thinking about being in nature All of a sudden, I thought that I had to go a little quicker (laughs), or the treadmill may stop.” *Female, 20 years, 360° video*
3. Qualities of the IVN landscape 3.1. Familiar and calming[a] 3.2. Summer season[a] 3.3. (Bio)diversity and wildness of landscapes[b]	“(…) I really like Glomma [name of the river]. I have a boat there and I spend a lot of time there (…). It is a very peaceful place, and I can relax in that environment.” *Female, 20 years, 360° video* "(…) It is the season [summer] that I liked very much that it felt like light, I didn’t think about the fact that it was digital light that I saw (…) for me it could just as well have been sunlight, it felt like it." *Male, 29 years, 360° video*	"(…) I can kind of imagine that it could have been even more exciting if there had been more details and things like that (…) maybe more birds." *Female, 63 years, 360° video* “I thought it was nice with the river, but I think I would have preferred to have more diversity (…) I think I would have liked it more to walk in the forest or possibly some kind of mountain tour.” *Female, 21 years, 3D model*
4. Affective and physical responses 4.1. Restoration (affect, mood, and memory recall)[a] 4.2. Physical activity[a] 4.3. Benefits for vulnerable groups[a]	“It was really pleasant that there was so much light. Also, I never really thought about that it would be possible to go indoors on a treadmill, but still feel to be outdoors. It was a very nice experience (…) and a nice way to disconnect from my thoughts. (…) Just getting these 10 min’ walk, made me feel more motivated for the rest of the day.” *Female, 21 years, 3D model* “It really made me think about how lovely it is in the summer, with green lawns and green leaves and the wind blowing without it being cold, and I live right next to (that river) myself (…). So, I got some associations.” *Female, 20 years, 360° video* “(…) it can give people who don’t have the opportunity to go out the opportunity to experience nature anyway.” *Female, 63 years, 360° video*	“I felt that I panicked a bit inside this little bubble.” *Female, 21 years, 3D model*

[a] Facilitators.
[b] Barriers.

suggest that the IVN technology could provide the opportunity to experience nature among those who, for various reasons, cannot visit actual nature.

4. Discussion

4.1. Effects and experiences of the IVN exposure

The analysis of the quantitative data showed a statistically significant increase in the ratings of CNS in both IVN conditions, as opposed to the control condition, which showed no significant changes. These findings are in line with previous literature, as highlighted by a recent meta-analysis showing that indirect (including digitally mediated) nature experiences significantly and consistently elicit increased nature connectedness in adults (Sheffield et al., 2022). The analysis of the qualitative data provided further insights on the individuals’ perceptions and experiences during the IVN exposure, shedding light on possible pathways underlying the observed increments in CNS. In particular, as highlighted by the theme “IVN as present and distinct experience,” the experiencing nature through IVN appears to be more than a mere surrogate of being out in nature. IVN experiences appears to have its own value, a way for people to temporally disconnect from their everyday life and be transported into a fantastic world. Although participants consciously perceived the IVN as fictitious and different than being in actual nature, the sensations they described were positively evaluated. This is somewhat in contrast with previous conceptual analysis which proposed that the benefits and value of IVN technology (and digital nature more in general) would be dependent to the extent to which it can realistically simulate an actual natural experience (Litleskare et al., 2020).

As highlighted by the emerging theme “Qualities of the IVN landscape,” it transpires how the participants’ experience was shaped by the extent to which they could recognize comforting nature landscapes and elements (subcode “Familiar and calming”) and elicit positive associations (subcode “Summer season”). This is in line with previous analyses emphasizing the effectiveness of IVN as a powerful tool to facilitate *savouring*, a person’s ability to appreciate and enhance a positive experience (Bryant & Veroff, 2017), which can be prolonged and boosted by viewing known landscapes (Filep et al., 2013; Litleskare et al., 2020). Accordingly, as emerging from the theme “Affective responses,” besides reporting emotions and sensations that are highly similar to those one may expect in actual nature (subcodes “Physical activity” and “Restoration [affect, mood]”), participants also explicitly described how IVN made them recall previous experiences in actual nature (subcode “memory recall”). This is in line with a recently proposed theoretical framework postulating that “associated environmental cues” such as synthetic reproductions of nature (e.g., IVN) would trigger generalized conditioned responses formed during previous repeated experiences (Egner et al., 2020). In this respect, as past experiences in nature are paramount for people’s sense of nature connectedness (Calogiuri, 2016; Rosa et al., 2018; Soga et al., 2020; Thompson et al., 2008), IVN may foster nature connectedness by capitalizing on individual’s past experiences, rather than generating novel sense of identity with the natural world.

4.2. Visualization techniques: 360° video vs. computer generated IVN

In spite a slightly larger effect size in favour of the 3D model condition, we found no statistically significant differences between the two types of IVNs when comparing CNS expressed as delta values. In keeping with this, the qualitative findings did not highlight any relevant differences in the experiences of the participants who underwent either the 360° video or the 3D model conditions. This partly contradicts previous findings by Yeo et al. (Yeo et al., 2020), who found a marginally significant greater increases in nature connectedness after exposure to a computer generated IVN compared to a matching 360° video.

Importantly, unlike the study by Yeo et al. (Yeo et al., 2020), in our study the two IVN conditions had equal levels of interactivity, which provides the ground for clarifying the actual impact of the visualization technique. In this respect, it is important to stress the fact that, while 360° videos may not be intrinsically less effective than computer-generated IVNs, as 360° videos are most commonly characterized by lower levels of interactivity, the potential of these types of IVNs in interventions that aim at promoting nature connectedness in different groups of the population may be limited.

The issue of immersion and presence was also evident in the qualitative strand of our study (theme "IVN as present and distinct experience," subcode "Sense of reality," and theme "Impact of technical equipment," subcode "Level of immersion"). The participants generally reported to appreciate the extent to which the technology made them feel present in the virtual world, which seems to have greatly impacted their overall experience. Accordingly, flaws in the overall immersiveness (e.g., the physical sensation of being on the treadmill and wearing the VR headset) disturbed the sense of presence and were generally negatively connotated. While this speaks to the users' experience in a more general perspective, it may have also influenced the effectiveness to specifically elicit feelings of nature connectedness.

4.3. Do IVN experiences actually elicit nature connectedness?

The pre-post changes for the 360° video and the 3D model showed a medium-large and large effects size, respectively. These findings are in accordance with effects sizes reported in a recent meta-analysis (Sheffield et al., 2022), although the meta-analysis also highlights that the effect size of IVN-mediated nature experiences varied greatly depending on the specific study, ranging from small (Hedges $g = 0.17$) to large (Hedges $g = 0.84$). Interestingly, these values were highly similar to studies examining the effects of experiences in actual nature, suggesting that IVN may be (at least in terms of effect size) as effective as direct nature experiences in acutely eliciting increased state levels of nature connectedness. A question arises, however, regarding the *quality* of such effects. The qualitative findings of the present study provide valuable insights in this respect.

The participants recurrently lamented how IVN technology cannot provide the full range of experiences and sensations that one can experience in actual nature (smells, haptic sensations, flavours, thermoception). While this clearly diminished the IVN experience, it may also contribute to commodifying and degrading people's appreciation of the outdoors. Being in actual nature is not always pleasant; cold/hot or wet weather, annoying insects, potential dangers, etc. are often negatively eveluated by many people. Learning to appreciate such nuanced experience can be rewarding, but it requires being exposed to the elements. While IVN could be the only way to experience nature for some people (e.g., people who, for various reasons, cannot engage with outdoor nature), having IVN as the sole way to interact with nature carries inevitably large experiential losses. In the words of Kahn (Kahn, 2018, p. 163), "with at best technological nature as a substitute for the real thing, we will be shifting the baseline downwards–as we have already–for what can be consider as physically and psychologically healthy humans."

The IVNs used in the present study depicted an urban green space. The choice of this particular place was partly due to current technical limitations associated with the generation of IVNs. For instance, this specific environment allowed to film a 360° video with minimal turns and scene oscillations, hence reducing the risk of cybersickness (Litleskare & Calogiuri, 2019; Lo & So, 2001). The landscape contained limited number of complex elements such as trees and bushes, allowing to reproduce it photorealistically whilst avoiding the 3D model being too taxing for the computers processing capacity. At the same time, the scenario used in the present study was previously found to have desirable restorative characteristics, with the potential to induce significant improvements in psychological states (Calogiuri et al., 2018). Moreover, the presence of water (Barton & Pretty, 2010; Gascon et al., 2017) as well as the high levels of prospect (Gatersleben & Andrews, 2013) that characterized the environments were also deemed as advantageous for eliciting positive emotional responses. However, as experiences in wild environments can elicit positive psychological responses to a greater extent than experiences in urban nature (Li et al., 2022), it is plausible to assume that an IVN depicting a landscape with fewer traces of human activities (for example a forest) might have elicited even greater increments in nature connectedness than those observed in our results. This assumption finds correspondence in the qualitative findings, with the theme "Virtual landscape" shedding light on barriers to an effective experience, such as the lack of "(bio)diversity" and "wilderness." Beyond this, appreciation of (bio)diversity and wilderness is an important aspect of a *genuine* sense of connectedness with the natural world. Like in the case of this study, IVN scenarios tend to represent less biodiverse and more "combed" natural landscapes, which may distort people's understanding of nature. Levi and Kocher (1999) warned about this possible side effect of IVN technology, presenting evidence of how this may result in a de-evaluation of local natural environment or, in general, environments that do not reflect the unrealistic aesthetically expectations reinforced through IVN. In this sense, the increased feeling of nature connectedness one may experience after exposure to IVN may be artificial or ungenuine. Hence, IVN may contribute to *disconnecting* people from nature at a deeper level. As Levi & Kocher pointed out, "the value of nature is more than the experiential and recreational benefits it provides to people. Nature provides a variety of benefits beyond human's immediate experience; nature exists and has value separate from human beings" (Levi & Kocher, 1999, p. 224).

4.4. Strengths and limitations

The present study advances the current debate on the way in which the visualization techniques impact the effectiveness of IVN technology, as well as how subjective perceptions and experiences support the initiation of enhanced feelings of nature connectedness through IVN. The present research aligns with the scope of the research agenda set by Frumkin et al. (2017), addressing three of the research priorities emphasized within the domain "Technological nature". The RCT was pre-registered, including information of planned statistical analysis and publication of findings, reducing the overall risk of bias. The qualitative analysis was conducted according to rigorous and transparent methodological procedures. Through a mixed-methods approach we could take advantage of the strengths of different research traditions, reducing biases and blind spots and gaining a more holistic and in depth understanding of the effects of IVN on nature connectedness. We employed state of the art technology, with the different IVNs closely matched in terms of interactiveness and environmental characteristics displayed. In spite of these strengths, a number of limitations must take into considerations.

The inclusion of a qualitative strand based on in-depth interviews provides novel and unique insights in this particular field. A previous study that included qualitative perspective did so mainly by including open-ended questions in their survey instruments (Spangenberger et al., 2022). However, one of the main weaknesses of the study consist in the small number of informants (only five) participating in the in-depth interviews. A larger sample might have provided richer material for analysis, possibly better highlighting differences in the perceptions associated with the two visualization techniques. Hence, the outcomes of the qualitative strand should be considered primarily as explorative, and caution is warranted when attempting to draw conclusions from this analysis.

Another limitation resides in the fact that this research was conducted during the Covid-19 pandemic, which was shown to influence both visitation and people's perceptions of natural environments. For example, evidence suggests an increase in nature visits during lockdown, with participants reporting more positive perception of nature (Kanelli et al., 2021; Lenaerts et al., 2021). Such changes in perceptions of nature might extend to IVN as well. To the best of the authors' knowledge, no study has documented an impact of the Covid-19 pandemic on IVN and nature connectedness. However, an impact of the pandemic on our findings cannot be confidently dismissed. Finally, the sample comprised healthy adults with relatively high levels of nature connectedness at baseline. Other groups of people with lower levels of nature connectedness and that are less likely to visit real nature may benefit more from an IVN, due to a potential "ceiling effect" in some of our participants.

4.5. Recommendations for future research

This particular study aimed at providing foundational knowledge on how different visualization techniques influence the way in which IVN can influence people's nature connectedness. This particular filed is at its very infancy, the authors purposefully limited the number of experimental conditions included, so that mayor focus could be given to the topic at hand whilst reducing possible confounders. However, the authors acknowledge the need of further exploring the many other aspects that remain unexplored in this study. In particular, the authors invite researchers interested this field to include more and/or different experimental conditions. The comparisons relative to the following variables are deemed as particularly meaningful within this field: type of environment (e.g., natural vs. urban), impact of bodily movements (i.e., sedentary exposures vs. exposure combined with some form of physical activity), duration of the exposure (i.e., shorted vs. longer exposures), different characteristics of the natural environments (e.g., "wilder" vs., more "urbanized" nature), different characteristics of the soundscape (e.g., more or less diverse sounds of nature), different visualization styles of the computer-generated scenarios (e.g., photorealistic vs. artistic representations), or different levels of resolution of the 360° videos. Studies comparing exposure to actual environments with corresponding IVN (or virtual exposure to other types environments) generated using different visualization techniques are also recommended.

5. Conclusions

The findings of the present study provide further evidence on the effectiveness of IVN as a tool to elicit acute changes on state nature connectedness among healthy adults. Additionally, as a novel contribution to the field, the study demonstrates that IVN created using different visualization techniques (e.g., 360° videos or computer-generated scenarios), can be equally effective in eliciting increased nature connectedness, assuming that equal levels of interactivity are provided. The integrated qualitative and quantitative findings of this study highlight how IVNs may be perceived as a present and distinct experience, not just a (poor) simulation of actual interactions with nature. Technical aspects of the IVN equipment, the qualities of the virtual landscape, and the individuals' affective and physical responses contribute to shaping such experience. More research is needed to investigate the extent to which IVN experiences may contribute to long-term changes in trait nature connectedness, as well as whether such increments correspond to a *genuine* sense of connectedness with and appreciation of the natural world.

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Data sharing

The datasets generated during the current study are available from the corresponding author on reasonable request.

Authors' contributions

G.C., conceived and designed the study, drafted the overall manuscript, led the team of authors, conducted the quantitative analyses. E.P., in collaboration with A.H., conducted the qualitative analysis and wrote the sections relative to this part. A.H. designed and conducted the in-depth interviews. O.E.F., and F.F., in collaboration with G.C. and S.L., developed the VR installations specifically for and in compliance with the study's purposes, and contributed writing and revising the sections relative to this part. S.L. provided substantial contribution in the conception and design of the study, conducted the experiments, and contribute revising all parts relative to the quantitative strand. All authors provided substantial contributions to the conception of the study, interpretation of the results, and/or writing of the manuscript, and approved the final version of the manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that did not use any generative AI and AI-assisted technologies in the writing process.

Conflicts of interest

The authors declare no conflict of interests.

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