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Audio-visual-olfactory immersive digital nature exposure for stress and anxiety reduction: a systematic review on systems, outcomes, and challenges

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Evidence supporting the benefits of immersive virtual reality (VR) and exposure to nature for the wellbeing of individuals is steadily growing. So-called digital forest bathing experiences take advantage of the immersiveness of VR to make individuals feel like they are immersed in nature, which has led to documented improvements in mental health. The majority of existing studies have relied on conventional VR experiences, which stimulate only two senses: auditory and visual. However, the principle behind forest bathing is to have one stimulate all of their senses to be completely immersed in nature. As recent advances in olfactory technologies have emerged, multisensory immersive experiences that stimulate more than two senses may provide additional benefits. In this systematic literature review, we investigate the multisensory digital nature setups used and their psychological and psychophysiological outcomes; particular focus is placed on the inclusion of smells as the third sensory modality. We searched papers published between 2016 and April 2023 on PubMed, Science Direct, Web of Science, Scopus, Google Scholar, and IEEE Xplore. Results from our quality assessment revealed that the majority of studies (twelve) were of medium or high quality, while two were classified as low quality. Overall, the findings from the reviewed studies indicate a positive effect of including smells to digital nature experiences, with outcomes often comparable to conventional exposure to natural environments. The review concludes with a discussion of limitations observed in the examined studies and proposes recommendations for future research in this domain.

KEYWORDS

virtual reality, natural environment, olfactory stimuli, multisensory virtual reality, psychological outcome, psychophysiological outcome, stress/anxiety, relaxation

1 Introduction

In today's world, stress and anxiety have emerged as pervasive global problems, particularly in the wake of the COVID-19 pandemic, which further contributed to the crisis with employment instability, reduced socialization, and increased financial pressures. Several studies have reported an unprecedented surge in mental health disorders (Smith B. M. et al., 2020; Pietrabissa and Simpson, 2020; Millroth and Frey, 2021). For example, relative to the pre-COVID-19 era, there has been a global rise of 25.6% in anxiety and 27.6% in depression, highlighting the urgency and significance of addressing mental health issues

(Hawes et al., 2021; Santomauro et al., 2021). The detrimental impact of these psychological challenges on mental wellbeing and overall quality of life has prompted a growing need for effective interventions, especially non-pharmacological ones.

One non-pharmacological intervention that has shown great promise is to immerse oneself in nature, which has been shown to reduce stress/anxiety states and to provide different mental health benefits (Giannico et al., 2021; Kotera et al., 2021; Yao et al., 2021), as well as changes in physiological signals (Corazon et al., 2019; Fu et al., 2022). In Japan, for example, the practice of engaging in multisensory nature immersion has been embraced for many years and is known as 'forest bathing' (Shinrin-yoku) (Hansen et al., 2017), where one spends time in a forest to enhance health, wellness, and happiness. Despite these well-documented benefits, exposure in natural environments may not be accessible to many, such as individuals with limited mobility or hospitalized patients. The World Health Organization estimates that about 15% of the world's population faces disability, including limited mobility. Additionally, it is known that approximately 55% (in 2017) of the global population resides in urban areas, where access to natural surroundings can be challenging. Projections suggest that this percentage will rise to 68% by the year 2050 (Ritchie and Roser, 2018).

One promising solution that has emerged that provides more inclusive access to nature is that of immersive virtual reality (VR). Immersive VR experiences can simulate real-life environments, allowing users to feel present, and replacing their real surroundings with virtual reproductions. Numerous studies have explored the effects of VR in medical and healthcare (e.g. (Birckhead et al., 2019; Hao et al., 2022)). More recently, the concept of virtual nature bathing has also emerged. The approach is commonly referred to as 'digital Shinrin-yoku' (Reese et al., 2022) and aims to recreate the experience of nature exposure but in a virtual setting.

Virtual nature bathing experiences can vary widely and may involve 360-degree videos of nature environments projected onto head-mounted displays, panoramic photos shown on computer screens, or projections on walls, where users can feel immersed in the forest. As can be seen, these experiences primarily focus on visual and auditory stimuli, where nature scenes (e.g., forests, beaches, waterfalls, lavender fields) and sounds (e.g., birds chirping, leaves rustling, and water flowing) are present. Of course, the sense of immersion and presence are usually modulated by manipulating the quality of the visual (e.g., 8k-resolution high-fidelity 360-degree videos *versus* human-generated synthetic environments) and auditory (e.g., stereo *versus* 3D-audio) inputs.

Based on the principles of shinrin-yoku, however, the health benefits are believed to arise from the stimulation of all senses and complete immersion in nature. Since current VR systems offer only audio-visual stimuli, existing experiences may not be fully immersive and may not be providing maximal benefits to users. Indeed, research has revealed remarkable sensitivity of memory and the sense of presence to olfactory stimuli (Herz, 1998; Chu and Downes, 2002; Munyan et al., 2016), as well as to relaxation (Igarashi et al., 2014a; b; Amores et al., 2018). Smells have also shown to improve attention (Raudenbush et al., 2009; Dozio et al., 2021) to elicit basic emotions, such as happiness Vernet-Maury et al. (1999). In VR, it has also been shown to improve relaxation states (Carulli et al., 2019), to positively influence affective and behavioral reactions to the virtual environment (Flavián et al., 2021), to increase user engagement (Brengman et al., 2022) and sense of realism (Khan and Nilsson, 2023).

Given these insights, there is a compelling rationale to integrate olfactory stimuli in immersive nature exposure experiences, thus moving closer to the multi-sensory nature immersion aspect of Shinrin-yoku with an increased sense of presence, realism, and immersion. While recent studies have documented the impact of VR-based digital nature experiences on various psychological and physiological factors (e.g. (Jo et al., 2019; Syed Abdullah et al., 2021; Lee et al., 2022)), to the best of the author's knowledge, a review on multisensory digital nature exposure where smells are also included has yet to be published. Moreover, as digital nature exposure is aimed primarily at promoting relaxation, mindfulness, and connection with nature, existing reviews lack insights on how faithful the experiences are in achieving the immersion needed to reduce stress and anxiety. In this paper, we aim to fill these gaps. In particular, we explore studies that have investigated audio-visual-olfactory digital nature exposure for stress/anxiety reduction, as well as the use of objective measures to quantify the reduction. The review presents findings on the systems used as interventions, the psychological and physiological effects associated with these interventions, and the limitations that they bring.

2 Methodology

The present systematic review was conducted according to the preferred reporting items for systematic reviews and meta-analyses (PRISMA) Page et al. (2021) guidelines, as detailed in the sections below.

2.1 Search strategy

The research was conducted across six databases, including PubMed, Science Direct, Web of Science, Scopus, Google Scholar, and IEEE Xplore, between January 2016 to April 2023. The following keywords were used: (stress OR anxiety OR relaxation) AND ("virtual reality") AND ("nature scene" OR "digital nature" OR "digital forest" OR "virtual forest" OR "virtual nature" OR "forest bathing" OR "forest therapy" OR "nature therapy" OR "shinrin-yoku" OR "natural environment") AND (olfactory OR aromatherapy OR olfaction) AND (EEG OR biosignal OR physiological OR multisensory). Keywords were searched throughout the title, abstract, and full text of the articles. Although we have not included the term "psychological" as a keyword, we have kept articles that only used subjective measurements through questionnaires, so that we can analyze the systems that were used and quantify any limitations.

2.2 Inclusion and exclusion criteria

We included articles that 1) created a VR experience with or without head-mounted displays (HMD), i.e., such as screens or projectors; 2) included olfactory stimuli in the study; 3) included natural scenes as the virtual environment, e.g., forests, parks, and beaches; 4) included experiments with healthy patients; and 5) provided qualitative and/or quantitative outcome measures. In turn, exclusion criteria included: 1) review papers, books, or book chapters; 2) studies that did not use natural environments with a focus on relieving stress/anxiety and promoting relaxation; 3) studies with fewer than ten participants; 4) studies without experiments with human participants; and 5) studies that used games instead of nature scenes.

2.3 Screening and data extraction

After collecting articles from each database, the Zotero tool was used to remove duplicate articles. Titles and abstracts were then screened to exclude unrelated articles. For full-text screening, two steps were performed: first, the keywords related to olfactory were searched in the text, to check if the article would be kept or not. After removing studies that did not include the olfactory stimulus, the second step was then performed on the remaining papers using the inclusion/exclusion criteria.

To collect detailed information from each study, we extracted the following data from each article: study information (first author, year of publication), demographics (number of subjects, gender distribution, age), study design (control group, exclusion criteria, target population, target problem, experiment description, stimulated sense), intervention (VR device, collected physiological (when applied), olfactory equipment, duration), and outcomes (psychological measurement indicators, results extracted from physiological measurements and follow-up findings).

2.4 Quality assessment checklist

To assess the risk of bias (ROB) in the included studies, we employed the National Institutes of Health—National Heart, Lung, and Blood Institute (NIH-NHLBI) quality assessment tool NHLBI (2022). However, since this tool is primarily designed for clinical studies, which does not perfectly align with the nature of the studies included in this review, we also used a modified checklist based on (1) the Joanna Briggs Institute Critical Appraisal tool for use in JBI Systematic Reviews Tufanaru et al. (2020), namely, the Checklist for Quasi-Experimental Studies (Non-Randomized Experimental Studies), and (2) the Checklist for Randomized Controlled Trials Tufanaru et al. (2020).

The modified checklist comprised nine items, namely,: (1) Random assignment of conditions, (2) Existence of a control group, (3) Similar demographics across conditions, (4) Reliability of outcomes measurement, (5) Statistical analysis, (6) Multiple outcome measurement points, (7) Sample size, (8) Results comparison pre and post intervention/exposure, and (9) Clear study objective (for more details, see Supplementary Table S2.

Each item was assigned a score of one if it was clearly mentioned or addressed, 0.5 if it was partially mentioned or partially clear, and 0 if it was not mentioned or unclear. From the modified checklist, the maximum score achievable is 9. Therefore, studies with scores equal to or below half (4.5) were considered low quality, those between five and 6.5 were considered medium quality, and those with a score greater than or equal to seven were considered high quality.

3 Results and discussion

3.1 Included studies

A total of 1,143 articles were identified, 1,019 were from Google Scholar, 14 from IEEEXplore, 68 from Scopus, 41 from ScienceDirect, one from Web of Science, and none from PubMed. Figure 1 depicts a flow chart of the study selection process. After eliminating duplicates, 814 studies were left to be screened based on title and abstract. From this first pass, 660 papers were eliminated as they did not meet the inclusion criteria, resulting in 154 articles included for full-length analysis. Of these, only 12 articles were considered relevant for the current review. Additionally, two articles were included based on the analysis of the references cited in the originally selected 12 articles. In the end, 14 articles focusing on multisensory VR using audio-visual-olfactory stimuli, nature-based digital environments, and focused on relaxation or restoring stress/anxiety were included in this review.

3.2 Study characteristics

The overview of the selected studies is divided into five different tables, which focus on the provided information about the study population (Table 1), general characteristics of the reviewed studies (Table 2), experiment design (Table 3), main outcomes (Table 4), and the reported restorative effects (Table 5).

3.3 Quality assessment

The detailed responses obtained from both assessment tools can be found in the Supplementary Material. Supplementary Table S1 displays the responses for the NIH-NHLBI quality assessment tool, specifically for before-after (pre-post) studies without a control group. Additionally, Supplementary Table S3 presents the results of the quality evaluation using the modified checklist described in Section 2.4.

The findings suggest that of the 14 studies assessed, six were rated as high quality, six were rated as medium quality, and two were rated as low quality. Most of the studies categorized as medium quality demonstrated elements such as a counterbalanced study design, measurement of both objective and subjective outcomes, and similarity in terms of demographics. However, certain aspects, such as the inclusion of a control group/condition, were not consistently addressed. Overall, we found the quality criteria to be satisfactory. For a more comprehensive understanding of the quality criteria, please refer to Supplementary Table S2.

As can be seen from the Tables, all studies had virtual nature exposure conditions including olfactory stimuli. The virtual nature environment included mostly forests, urban green spaces, beaches, and parks. The range of exposure was characterized by a wide variability. For example, some studies only cited the total experience

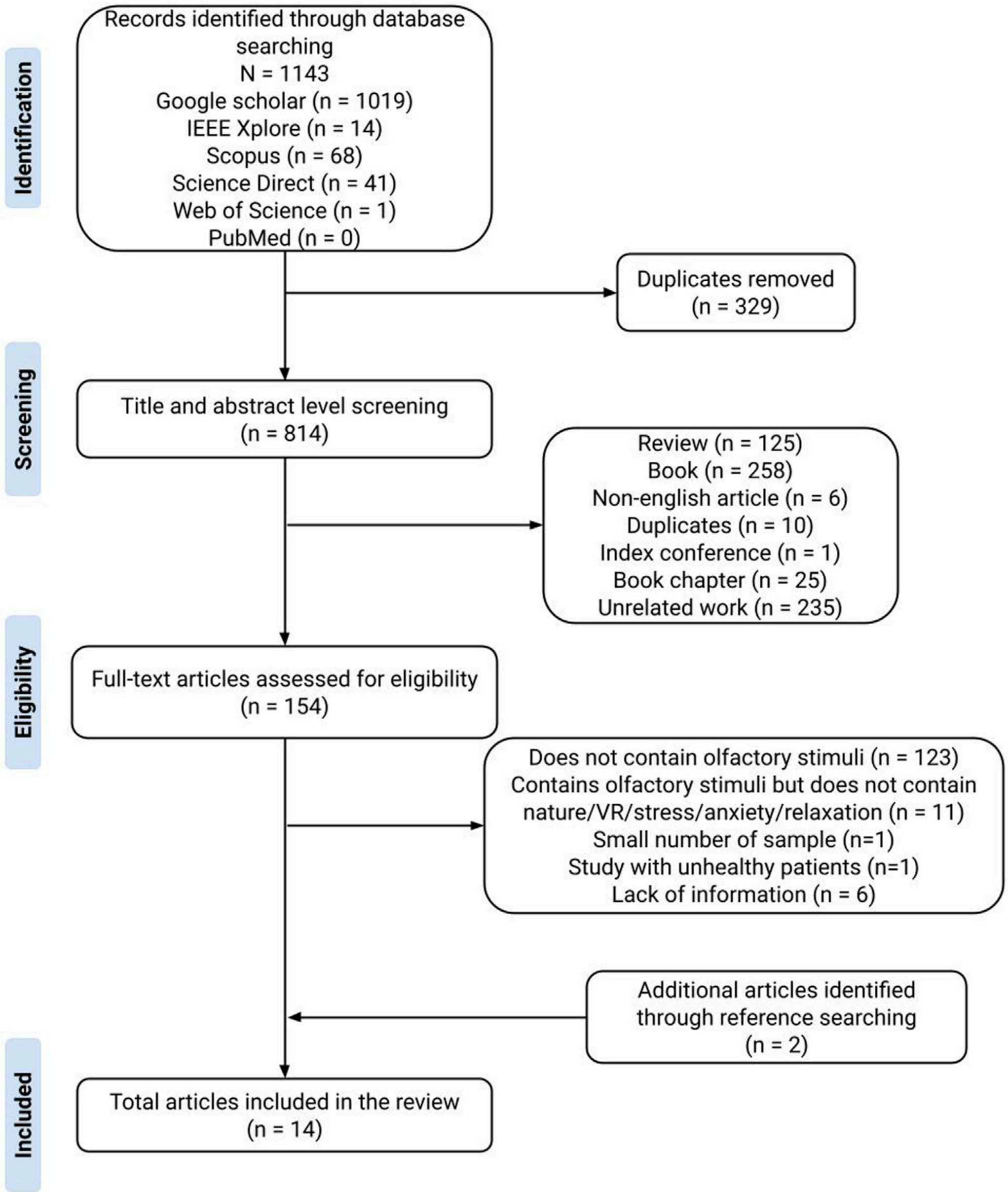

FIGURE 1
Flow chart of paper selection steps.

time, including the time to answer the questionnaires, and times ranged from a minimum of 5 min to a maximum of 1 h 30 min. Other studies, in turn, reported only the time of each condition, ranging from a minimum of 1 min to a maximum 60 min. Lastly, some reported both. In the next sections, more details are provided about the studies.

3.4 Multi-sensory stimuli and systems

3.4.1 Visual stimuli

Studies relied on different nature scenes for relaxation. In Zhang et al. (2023), for example, a panorama photo of Osmanthus trees (a common Chinese garden plant) was used for the intervention and a white wall without any smells as a group control. In Qi et al. (2022), four different environments were used, each presented as a three-dimensional 360-degree panoramic photo. The nature scenes included a lawn, a rose garden, an Osmanthus tree garden, and a pine forest. As in the other study, a white wall with no smell or audio was used for the control group. The work by Lopes et al. (2022) used a 360-degree computer-generated video of a forest environment; the study did not have a control group. The environment used in Abbott and Diaz-Artiles (2022) was a forested area including a campsite, a river, and a wood cabin; for the control condition, subjects were exposed to a stressful stimulus. In Schebella et al. (2020), a 360-degree video of low biodiversity, moderate biodiversity, and high

TABLE 1 Description of study population from the examined papers.

Study	Participants	N	Age range and/or mean ± SD	Female/Male
Zhang et al. (2023)	University students	95	18-26 years old	71/24
Shin et al. (2022)	University students	88	18-24 years old 20.0 ± 1.3	entire sample (F:54; M: 34); no window (F: 21; M: 13); closed window (F: 14; M: 13); open window (F: 19; M: 8)
Qi et al. (2022)	Undergraduate and graduate students	308	18-31 years old 22.92 ± 2.20	268/40
Lopes et al. (2022)	University students	16	27 ± 7.46	6/10
Takayama et al. (2022)	Members of the public	25	36.1 ± 8.13	13/12
Zhao et al. (2022)	University students and staff	38	27.7 ± 11.1	13/25
Abbott and Diaz-Artiles (2022)	University students	10	23.1 ± 2.8	3/7
Schebella et al. (2020)	University staff, students and members of the public	52	37.6 ± 10.6	28/24
Putrino et al. (2020)	Frontline healthcare workers	496	Not mentioned	Not mentioned
Song et al. (2019)	University students	21 female	21.1 ± 1.0	Only F
Hedblom et al. (2019)	Members of the public	154	city (mean age 27); park (mean age 28); forest (mean age 27)	city (F: 28; M: 22); park (F: 26; M: 26); forest (F: 28; M: 24)
Sona et al. (2019)	Students	122	22.69 ± 2.23	64/58
Amores et al. (2018)	Not mentioned	12	28.2 ± 4.4	4/8
Serrano et al. (2016)	Members of the public	136	27.05 ± 8.01	84/52

biodiversity nature scenes was used, along with a virtual urban environment as a control condition. In Hedblom et al. (2019), 360-degree photos of a park and forest were used, while for the control condition, an urban environment was used. Lastly, in Amores et al. (2018), a beach scene was presented in 360-degree video format. For the control condition, it was mentioned that no stimulus was presented and no specific instructions were given to the participants, other than to not close their eyes.

While the studies above used HMDs as the display modality, other studies relied on projectors and display screens/TVs to provide the virtual experience. In Takayama et al. (2022), a video image of a forest environment was projected in a room. In Shin et al. (2022), a 270-degree video of a busy cafe scene was presented under three conditions, two of which included a nature scene. In Zhao et al. (2022), an LED display screen was used to transmit a video of a forest in autumn colors; the control condition had no stimulus. In Putrino et al. (2020), a high-definition projector was used to show a soothing natural landscape, comprised of either ocean scenes or forest scenes. In Song et al. (2019), a 4K-compatible display television was used and the visual stimulus was a photograph view of a forest landscape. The work in Sona et al. (2019), utilized an artificial window comprised of three high-resolution 4K LED screens with speakers to present a park scene and a lounge scenario. In Serrano et al. (2016), an HD video projector was used where participants could watch relaxing scenes, including a beach and a landscape covered in snow. Lastly, the studies in Putrino et al. (2020); Sona et al. (2019) relied on a hybrid setting, where real plants were also used. More details about the virtual environment presentation modality can be seen in Section 3.5.

3.4.2 Auditory stimuli

Audio stimuli were used in most of the studies, with only two studies focusing on the visual-olfactory senses Zhang et al. (2023); Song et al. (2019). The audio was related to nature and often included bird and water sounds. Among the selected articles, only three studies used complementary sounds, in addition to nature ones: Lopes et al. (2022) included a guided self-reflection message presented in a young woman's voice; Putrino et al. (2020) and Serrano et al. (2016) also included relaxing music. For the studies that used the control condition with urban environments Hedblom et al. (2019); Schebella et al. (2020), it was common for traffic sounds to match the environment. In Sona et al. (2019), only instrumental music was played. Finally, the work in Shin et al. (2022) compared an open window (with virtual nature) condition *versus* a closed window (with/without nature) in a coffee shop. In the open window condition, sounds of nature could be heard. In all three conditions, background babble noise, typical of a coffee shop, was also presented at a moderate volume level.

3.4.3 Olfactory stimuli

All scents used in the studies were related to nature for the intervention conditions with the natural environments. Some relied on natural scents, such as the work in Zhang et al. (2023), which used real osmanthus flowers to produce the olfactory

TABLE 2 Description of the characteristics of the reviewed studies.

Study	Pre- and post-physiological measurement	Control group/ Control condition	Study aim
Zhang et al. (2023)	yes	yes	Expound the relationship between garden plant smell scapes and human health
Shin et al. (2022)	no	yes	To measure the restorative qualities of windows with nature views in a busy setting
Qi et al. (2022)	no	yes	Examine effects on physio-psychological restoration on birdsong and multi-sensory combination
Lopes et al. (2022)	no	no	Explored the effects of ultra-reality multisensory digital nature walks on user relaxation and compared subjective and objective findings relative to a conventional audio-visual VR experience
Takayama et al. (2022)	yes	no	Investigated the physiological and psychological therapeutic effects of a digital shinrin-yoku environment constructed indoors
Zhao et al. (2022)	no	no	Present a multisensory workstation to improve productivity, restorative quality, and wellbeing in the open-plan office
Abbott and Diaz-Artiles (2022)	no	no	A multisensory virtual reality environment as a potential tool to maintain the long-term behavioral health of astronauts
Schebella et al. (2020)	yes	yes	Multisenrory immersive natural virtual environment comparing three levels of biodiversity as well as one urban environment
Putrino et al. (2020)	no	no	A multisensory nature-inspired relaxation space to assist healthcare workers
Song et al. (2019)	yes	no	Investigate the physiological effects on brain activity and autonomic nervous activity of forest-related visual, olfactory, and combined visual and olfactory stimuli
Hedblom et al. (2019)	yes	yes	Understanding the link between physiological mechanisms and qualities of urban green spaces. Compare the effects of visual stimuli to the effects of olfactory stimuli and auditory stimuli on physiological stress recovery
Sona et al. (2019)	no	yes	Test the restorative potential of sensory-enriched break environments in a between-subjects with repeated measures design, focusing on the type of environment (natural outdoor vs. built indoor environment) and sensory input (no sensory input vs. audio-visual input vs. audiovisual and olfactory input)
Amores et al. (2018)	yes	no	A virtual reality experience that integrates a wearable, low-cost EEG headband and an olfactory necklace that passively promotes relaxation
Serrano et al. (2016)	no	no	To test the efficacy of a mood-induction procedure in a Virtual Reality environment for inducing relaxation and generating a sense of presence, and to test whether the stimulation of the senses of touch and smell improves the efficacy of this experience

stimulus, and the work in Qi et al. (2022) which used real samples of lawn, rose flowers, osmanthus flowers, and pine. In Song et al. (2019) they used Hinoki cypress leaf oil (Kiseitec Co., Wakayama, Japan) extracted by steam distillation from leaves and twigs of Hinoki cypress trees. On the other hand, eight studies used different types of diffusers to emit smells. In Takayama et al. (2022), the essential oil of Abies sachalinensis (Sakhalin fir) was used. The authors in Shin et al. (2022) used two ultrasonic essential oil diffusers with the aroma of coffee and wet dirt (nature condition). In Zhao et al. (2022), the Aroma Shooter device was used to provide a forest scent. In Abbott and Diaz-Artiles (2022), scents were produced with the Olorama Scent Generator (Olorama Technology Ltd, Spain) and smells of sausage, coffee, wet ground, pine, woods, roses, lavender, and honey were used. In Putrino et al. (2020), yuzu, hinoki, roman chamomile, and lavender essential oils were used. In Sona et al. (2019), scents of rosewood, geranium, ylang-ylang, olibanum (frankincense), and hyssop were used in the natural outdoor condition and composition of rosewood and cardamom in the indoor condition. In Serrano et al. (2016), a lavender scent was distributed with a ceramic diffuser. In Lopes et al. (2022) a SENSIKS (SENSIKS, Netherlands) multisensory pod was used with scents of dirt, forest, and grass.

Lastly, three studies used their methods of aroma emission. In Schebella et al. (2020), scents were applied to cotton pads and attached to the HMD, a range of 16 nature scents (e.g., several types of grass, soil, leaves, and flowers) and four urban scents (e.g., dust and turpentine) were initially tested on a convenience sample of 11 people. In the end, they used only one scent in the urban and low biodiversity scenes, and three different natural scents in the high

TABLE 3 Description of experimental design of reviewed papers.

Study	Conditions	Type of VR (device)	Virtual nature environment	Stimuli	Scent device	Scent used	Duration
Zhang et al. (2023)	Only olfactory vs. Only visual vs. Visual and Olfactory	Pico (but not mentioned)	Panorama photo of Osmanthus trees	visual olfactory	Small container	The flowers of Osmanthus fragrans var	34 min total. 3 min VR environment
Shin et al. (2022)	Brick wall view vs. closed window nature view vs. no open window nature view	Projector	VR simulation of a busy university cafe along with indoor sounds playing in the background and the scent of coffee. Birdsongs and dirt smells were added to the open window condition	visual auditory olfactory	Two ultrasonic essential oil diffusers	Cafe and the aroma of wet dirt	6 min VR environment
Qi et al. (2022)	Only birdsong vs. birdsong + photo (4 types) vs. birdsong + odor (4 types) vs. and birdsong + photo + odor (4 types)	Pico Goblin VR	3D 360-degree panoramic photo: Lawn, rose garden, osmanthus tree garden, and pine forest	visual auditory olfactory	Small container	Leaves from the lawn, flowers of rose bushes, flowers of osmanthus trees and leaves (pine needles) of pine trees	25 min total. 2 min VR environment
Lopes et al. (2022)	Audio-visual only vs. ultra-sensory	Oculus Quest	360-degree video, forest environment	visual auditory olfactory tactile	SENSIKS	Dirt, forest and grass	1min15seg VR environment
Takayama et al. (2022)	Digital forest	Projector	Video images taken in Urahoro-cho, Hokkaido, on the three walls and ceiling of the experimental room	visual auditory olfactory	Diffuser	Essential oil of Abies sachalinensis	1hr30min total. 20 min VR environment
Zhao et al. (2022)	Neutral vs. Forest without scent vs. Forest with scent	LED display (screen)	Video of a forest in colorful autumn color	visual auditory olfactory tactile	Aroma Shooter from aromajoin	Forest scent mixture	1hr5min total. Tutorial of an example session and several cognitive tasks (approx. 20 min). Experiment session (approx. 45 min)
Abbott and Diaz-Artiles (2022)	VR condition without scents vs. VR condition with scents	HTC Vive Pro	Nature inspired VR environment with localized scents and sounds featuring a rushing river, campground, and small cottage	visual auditory olfactory	Olorama Scent Generator (OSG)	Sausage, coffee, wet ground, pine, woods, roses, lavender, honey	Stress stimuli (8 min each). Nature VR environment (15 min each condition)
Schebella et al. (2020)	Urban vs. low biodiversity vs. moderate biodiversity vs. high biodiversity vs. high biodiversity (visual-only)	Oculus Rift	360-degree video of urban, low biodiversity, moderate biodiversity, and high biodiversity	visual auditory olfactory	Cotton pads attached to the head-mounted display	Not specified. The urban and low biodiversity: single scent; high biodiversity: three different natural scents	15 min baseline; TSST total 15 min; 5 min VR environment
Putrino et al. (2020)	Recharge Room	HD projector	Natural scenes (not specified in the paper)	visual auditory olfactory	Diffuser	Yuzu, hinoki, roman chamomile, and lavender essential oils calming scents	15 min experiences
Song et al. (2019)	Visual stimulus vs. olfactory stimulus vs. combined stimulus	4K display television	Forest landscape of Hinoki cypress trees	visual olfactory	Unspecified device	Hinoki cypress leaf essential oil	90s each condition
Hedblom et al. (2019)	Urban vs. park vs. forest	Oculus Rift	2D 360° Virtual Reality photos of urban area in Stockholm; park in Uppsala; city forest in Uppsala	visual auditory olfactory	Computer-controlled olfactometer	Urban: diesel, tar, and gunpowder; Park: grass; Forest: two evergreen species and mushroom	5 min 30s total

(Continued on following page)

TABLE 3 (*Continued*) Description of experimental design of reviewed papers.

Study	Conditions	Type of VR (device)	Virtual nature environment	Stimuli	Scent device	Scent used	Duration
Sona et al. (2019)	No sensory input vs. audiovisual input vs. audiovisual and olfactory input	An artificial window LED screens with speakers	Park and lounge scenery	visual auditory olfactory	Diffuser	Rosewood, geranium, ylang-ylang, olibanum (frankincense) and hyssop in the natural outdoor condition. Rosewood and cardamom in the built indoor condition	65 min
Amores et al. (2018)	No stimulus vs. VR + Scent + Audio	Samsung Gear VR	360° beach video	visual auditory olfactory	Essence necklace	Lavender essential oil	5 min each condition
Serrano et al. (2016)	VR vs. VR + Smell vs. VR + Touch vs. VR + Touch + Smell	HD video-projector	House of Relaxation: affective pictures, a video-clip with a relaxing scene, relaxing music and narratives, sounds of nature, and autobiographical recalls	visual auditory olfactory tactile	Ceramic diffuser	Lavender essential oil	60 min for each condition

biodiversity scene, however, they did not specify the exact name of the aroma. All scents were selected from the Demeter Fragrance Library[1]. In Hedblom et al. (2019), the authors used their own computer-controlled olfactometer (Lundström et al., 2010), where city odors included diesel, tar, and gunpowder and for park odors they used grass and different forest odors, including two evergreen species and mushroom. In Amores et al. (2018), an essence necklace was used to emit a lavender essential oil scent.

The methodology for selecting scents in multisensory VR studies varies, often reflecting the unique objectives and contexts of each research project. For instance, Zhang et al. (2023) selected the scent of Osmanthus, a flower renowned as one of the ten most famous flowers in China, where the study took place, thus highlighting the cultural relevance for scent choice. Takayama et al. (2022); Song et al. (2019) focused on scents from trees that complemented the visual aspects of the VR environment, thus enhancing the sensory congruence for users. Other studies, however, such as that conducted by Putrino et al. (2020); Amores et al. (2018); Serrano et al. (2016), opted for scents such as lavender and Roman chamomile essential oils, chosen for their documented effects in reducing anxiety and stress in the scientific literature.

Qi et al. (2022) took it one step further and used a portable odor sensor (COSMOS XP-329 III R; Rank Value, range 0–2000) to measure and select odor concentrations that closely mimicked the landscapes used in the virtual environments. Schebella et al. (2020) engaged participants in the scent selection process, where 11 subjects identified which scents they found to more closely match the natural or urban settings in the experiment. Seven scents were accurately recognized and subsequently utilized in corresponding VR environments, ensuring the olfactory experience matched the visual setting. Moreover, Sona et al. (2019) not only referenced literature for scent selection but also conducted preliminary tests with 12 subjects to determine the intensity of ambient scents and identify perception thresholds. Other studies Shin et al. (2022); Lopes et al. (2022); Zhao et al. (2022); Abbott and Diaz-Artiles (2022); Hedblom et al. (2019), chose scents based on the landscapes in their experiments.

3.4.4 Tactile and somatosensory stimuli

In addition to the audio-visual-olfactory stimuli detailed above, three studies also investigated tactile/somatosensory stimuli. In Lopes et al. (2022), heating elements and four fans surrounding the sides, back, and front of the users, as well as acoustic vibrations on the user's seat were used. In Zhao et al. (2022), fans were mounted on the top of the table pointing toward the user's head and table surface, as well as infrared lights underneath the table were used for temperature control. Lastly, in Serrano et al. (2016), artificial grass was installed on the ground, allowing the participant to touch and feel it during the immersive VR experience.

3.5 Presentation modality and virtual nature experiences

3.5.1 Display/projector-based experiences

Among the selected studies, seven presented the virtual reality experience using display/projectors in an indoor setting (Serrano et al., 2016; Hedblom et al., 2019; Sona et al., 2019; Putrino et al., 2020; Shin et al., 2022; Takayama et al., 2022; Zhao et al., 2022). In Shin et al. (2022), three conditions were tested: no window (brick wall), closed window (nature view), and open window (nature view) with all conditions including the scene of a coffee shop. Participants were randomized into one of three groups. Participants were immersed in a 270-degree VR simulation within the laboratory. The participant's viewpoint featured a lifelike projection of the student union coffee shop, spanning the front and left walls. Additionally, the right wall showcased three distinct conditions. Throughout all conditions, a coffee fragrance and ambient

1 http://www.demeterfragrance.com/

TABLE 4 Description of reported outcomes of reviewed studies.

Study	Outcome assessment (psychological)	Outcome assessment (physiological)	Main results
Zhang et al. (2023)	None	Blood pressure; pulse pressure difference; pulse; EDA; EEG	The research suggests that integrating olfactory and visual stimuli from garden plants can enhance physiological relaxation and overall health more effectively than experiencing these stimuli in isolation
Shin et al. (2022)	PRS; and ROS	None	The study found that adding sounds and smells to virtual nature windows did not significantly enhance their restorative effects compared to experiences without these stimuli. However, it was observed that virtual windows showcasing nature views can still offer substantial restorative benefits in busy indoor environments
Qi et al. (2022)	STADI-S	ST; EDA; EEG	Audio-Visual (using birdsong) stimuli enhanced physiological restoration and perceived quality without affecting psychology, while olfactory stimuli adversely impacted physiological restoration but increased landscape attraction and harmony; combining both stimuli improved physiological aspects (noted in beta-EEG) and perceived quality, yet still had no psychological impact
Lopes et al. (2022)	Relaxation state from 1 (“Not relaxed at all”) to 5 (“Very much relaxed”)	ECG; ST; EDA; BVP; breathing signals	Significant changes in relaxation were achieved with the proposed system and changes in physiological parameters were also observed
Takayama et al. (2022)	POMS; PANAS; ROS; PRS	maximum and minimum blood pressure; pulse rate; salivary amylase activity; HRVHR.	During exposure, notable changes in physiological states were observed compared to the resting state, accompanied by significantly positive changes in psychological states
Zhao et al. (2022)	Questionnaire (a set of survey questions including the PRS)	HRV	Forest environments (with scent and without scent), were perceived more positively than a neutral condition, but the unscented forest condition showed slower stress development and better recovery
Abbott and Diaz-Artiles (2022)	PANAS; 6-item (STAI-6)	None	After the VR experience with added scents, participants showed significantly lower stress levels compared to the control condition, with a notable decrease in negative emotions and anxiety from both the stressed state and baseline when olfactory stimuli were introduced
Schebella et al. (2020)	VAS Biodiversity Experience Index (BEI). Kim and Biocca’s telepresence	EDA; HR. But EDA data were not included in the analysis	In low biodiversity environments with multisensory stimulation, there was a notable improvement in all wellbeing measures and reduced anxiety, with multisensory experiences leading to better overall wellbeing recovery compared to visual-only experiences
Putrino et al. (2020)	Single-item Likert-style measure of perceived stress	None	After the experience the stress level was significantly reduced
Song et al. (2019)	Questionnaire comprising 4-opposite adjectives	Oxyhemoglobin concentration using near-infrared time-resolved spectroscopy; HRV; HR	The study revealed that combined visual and olfactory stimuli significantly altered physiological responses and enhanced feelings of comfort, relaxation, and a sense of naturalness and realism among participants
Hedblom et al. (2019)	Subjective stress sensibility (4-point Likert); Pleasantness of the landscape (from 1 to 100)	EDA	The study revealed that park and forest environments significantly lowered stress levels, in contrast to urban areas which induced higher stress. Furthermore, it was observed that high pleasantness ratings were associated with reduced physiological stress responses, notably in response to olfactory and, to a lesser extent, auditory stimuli, but not in response to visual stimuli

(Continued on following page)

TABLE 4 (*Continued*) Description of reported outcomes of reviewed studies.

Study	Outcome assessment (psychological)	Outcome assessment (physiological)	Main results
Sona et al. (2019)	Rating (1: pleasant to 7: unpleasant); PRS; 6-point Likert scale (1 = little to 6 = extremely). fatigue, mood, and arousal	None	The study found that both natural and lounge environments were perceived as more pleasant and restorative than a standard break room, indirectly facilitating the recovery of personal resources like mood, fatigue, and arousal, especially when a scent was added to an audiovisual simulation
Amores et al. (2018)	RRS 1 ("Not relaxed at all") to 7 (Totally relaxed)	EEG (Relax score based on the Renyi entropy)	Subjective perception of relaxation increased when using a VR headset with the olfactory necklace, compared to not being exposed to any stimulus
Serrano et al. (2016)	Clinical Assessment Questionnaire; Beck Depression Inventory II; STADI-S; VAS; SAM; Presence SAM	None	The stimulation of the senses of touch and smell did not show a significant improvement of the mood- induction or the sense of presence

Note: Electrodermal activity (EDA); Electroencephalography (EEG); Electrocardiogram (ECG); skin temperature (ST); blood volume pulse (BVP); Heart Rate Variability (HRV); Heart rate (HR).

conversation noises were used at a moderate volume level. In the open window condition, the immersive experience was further enhanced by the sounds of birds chirping/singing in the background, accompanied by the aroma of wet dirt. In Takayama et al. (2022), participants were exposed to a 20-min digital shinrin-yoku environment that reproduced visual, auditory, and olfactory elements, each session accommodated a maximum of five subjects, and an adequate distance between individuals was maintained. Video images of a forest were projected onto three walls and the ceiling of the experimental room.

The work in Zhao et al. (2022) focused on multimodal augmentation via lighting, audio, video, airflow, heating, and scent elements to improve the productivity and wellbeing of workers in an open-plan office. In this work, a comparison was made between three conditions (neutral vs. unscented forest vs. scented forest), and a stress induction phase was also performed. For the neutral condition, the LED panels displayed no visuals, whereas for the other two conditions (with scent and without scent) a scene forest was displayed. Another study created a *recharge room* with multisensory (visual, auditory, and olfactory) nature-inspired experiences where healthcare workers could relax and reduce stress Putrino et al. (2020). The environment was carefully designed to evoke a serene natural setting. Silk imitation plants were strategically placed to simulate lush greenery, while scenes of natural landscapes were projected onto a blank wall. The ambiance was further enhanced by soft, color-matched lighting, which complemented the projected landscapes. High-definition audio recordings of nature sounds were combined with relaxing music. To complete the multisensory immersion, essential oils, and calming scents were diffused using an essential oil diffuser, heightening the impression of being fully surrounded by a natural environment.

The study in Song et al. (2019) employed four different conditions, each lasting 90 s, namely,: a forest landscape image featuring Hinoki cypress trees without any accompanying odor (visual-only), a gray image infused with Hinoki cypress leaf essential oil (olfactory-only), a forest landscape image of Hinoki cypress trees combined with the scent of Hinoki cypress leaf essential oil (combined stimulus), and a gray image without any odor (control condition). The study conducted by Sona et al. (2019) examined five distinct conditions, including a control condition with no window, sound, or scent. Additionally, two audio-visual conditions were assessed: a nature condition with a window displaying nature scenes, accompanied by bird sounds and neutralizing air/no scent, and a lounge condition featuring a window displaying a lounge scene, instrumental music, and neutralizing air/no scent. Furthermore, the study explored two audio-visual-olfactory conditions where scents were introduced as an additional element.

In Serrano et al. (2016), the experiment was performed in a VR-room, in which a virtual reality environment was created where participants were immersed inside a two-story house called *House of Relaxation*; the goal was to induce relaxation and a sense of presence and to analyze whether adding touch and smell altered the experience outcomes. Inside the environment, users could perform different actions, such as modifying the house's decoration, watching a video clip through a projector, changing the intensity of the lights and the color of the walls, opening or closing doors and windows, moving between the two floors of the house, moving or adding furniture, changing the ground to grass or sand, or change the exterior landscape to reflect another natural context (e.g., beach or snow). The lavender scent was used to stimulate the olfactory sense, and for the tactile stimulus, they used artificial grass. They compared four conditions: audio-visual, audio-visual-olfactory, audio-visual-tactile, and audio-visual-olfactory-tactile.

3.5.2 HMD-based experiences

The other seven studies relied on VR HMDs to present the visual stimuli (Amores et al., 2018; Hedblom et al., 2019; Schebella et al., 2020; Abbott and Diaz-Artiles, 2022; Lopes et al., 2022; Qi et al., 2022; Zhang et al., 2023). The most recent study compared three conditions, i.e., olfactory-only, visual-only, and visual-olfactory) to a control condition Zhang et al. (2023). The experiment took place in a room with white walls and ceilings, ensuring a consistent indoor environment to prevent the subjects' moods from being influenced by external factors, such as weather and light. In the control group, an odorless condition was maintained, with participants exposed to an image of a white wall, devoid of any stimuli associated with plant smells or garden landscapes. In the olfactory condition, participants experienced a natural concentration of fragrance emitted from Osmanthus fragrans. For the visual stimulus, a panoramic photo of Osmanthus trees was displayed. The visual-olfactory condition involved the combination of both visual and olfactory stimuli.

In Qi et al. (2022), a total of 308 volunteers participated in the study and were divided into 14 independent groups. These groups were designed to explore three different stimulus scenarios: audio-visual, audio-olfactory, and audio-visual-olfactory. Four plant landscapes (lawn, rose garden, osmanthus tree garden, and pine forest), with each landscape accompanied by its respective scent when olfactory stimuli were integrated, plus a single birdsong group (1 group) that visualized a white wall and received no odor stimulus, and a control group (1 group) of participants who viewed only a white wall (no birdsong and no odor). Each condition comprised 22 participants, ensuring an equal distribution across the study.

In Lopes et al. (2022), two conditions were compared: audio-visual and audio-visual-olfactory-tactile. Participants were seated inside a SENSIKS multisensory booth, which provided a fully immersive experience. In the audio-visual condition, participants were immersed in a forest environment for approximately 1 minute, accompanied by the soothing sounds of nature. Additionally, a soft voice of a young woman whispered in the background, prompting participants to engage in self-reflection on existence and consciousness. In the audio-visual-olfactory-tactile condition, scents of nature, such as dirt, forest, and grass were included, while fans and heating elements located on the sides, back, and front of the participant were used to simulate wind and sunlight matching the visual content.

Another study that showed a positive impact of introducing olfactory stimuli to reduce negative affect and state anxiety levels was the work in Abbott and Diaz-Artiles (2022). There, they analyzed an audio-visual and an audio-visual-olfactory condition with a task to induce stress between conditions. They built two VR environments using Unreal Engine 4. The first VR environment was designed as a nature-inspired forested area, complete with a campsite, a river, and a wood cabin. To enhance the immersion, realistic sounds of nature such as a rushing river and chirping birds were incorporated. Additionally, when olfactory stimuli were required, scents of nature were introduced. The second VR environment was specifically tailored for the stress induction portion of the experiment, known as the Trier Social Stress Test (TSST). This environment was modeled after a small auditorium, featuring approximately 30 static audience members. These virtual audience members remained passive throughout the session, providing no feedback to the subjects, whether positive or negative. Lastly, in Amores et al. (2018), a baseline condition (no stimulus) was compared to an audio-visual-olfactory condition. The participant was comfortably seated while wearing the Essence necklace, which emitted a fragrance of lavender. Participants were presented with a 360-degree video of a beach setting and the audio accompanying the video.

3.5.3 Nature vs. urban virtual environments

Two studies compared between a natural and an urban environment (Hedblom et al., 2019; Schebella et al., 2020). In Schebella et al. (2020), three natural environments, with different levels of biodiversity (low, moderate, and high) were compared to an urban environment control condition. A significant effect of multisensory biodiversity was observed on stress recovery related to the urban environment. Moreover, in Hedblom et al. (2019) an urban area was compared to an urban park and an urban forest. Each condition included audio-visual-olfactory stimuli appropriate for the scenes. The two virtual nature conditions resulted in greater stress reduction relative to the urban environment. The perceived pleasantness was associated with the olfactory and auditory stimuli, but not with the visual stimulus. The study suggested that olfactory stimuli may be better at facilitating stress reduction than visual stimuli and highlights the relevance of multisensory approaches for stress reduction.

3.6 Outcome assessment (psychological)

3.6.1 Subjective measures

In total, 13 studies performed subjective measurements to analyze the mood changes associated with the multisensory VR exposure. Four studies administered the Perceived Restorativeness Scale (PRS) to measure how restorative an environment was (Sona et al., 2019; Shin et al., 2022; Takayama et al., 2022; Zhao et al., 2022). In Sona et al. (2019), questions about mood, fatigue, and arousal (before and after exposure) were also measured. Two studies used the Restoration Outcomes Scale (ROS) to analyze the subjective restorativeness, where Shin et al. (2022) requested the questionnaire only after VR exposure, while in Takayama et al. (2022) the measurement was requested before and after exposure. Two other studies used a semantic differential (SD) method. In Qi et al. (2022), a survey concerning the overall quality evaluation of the environment was used, while in Song et al. (2019) the participant's subjective spatial impressions were collected via a questionnaire with four opposite adjectives, each evaluated on 13 scales.

Two studies measured mood with the Positive and Negative Affect Schedule (PANAS) (Abbott and Diaz-Artiles, 2022; Takayama et al., 2022). Two studies used the Visual Analogue Scale (VAS) before and after exposure. While in Schebella et al. (2020) VAS was used to measure the perceived stress, anxiety, insecurity, calmness, and happiness levels of the participants, in Serrano et al. (2016) it was used to evaluate levels of sadness, joy, anxiety, and relaxation moods. One study used the Profile of Mood States (Takayama et al., 2022). The State-Trait Anxiety Inventory (STAI) was used in two studies. In Qi et al. (2022), the full 20-item version was used, whereas in Abbott and Diaz-Artiles (2022) a modified version including only six-items was used. The work in Serrano et al. (2016) mentioned using the state scale of the STAI but did not report the results; instead, it reported results using the Self-Assessment Manikin (SAM) (before and after exposure) and the Presence Self-Assessment Manikin (after exposure).

Single-item measures were also used across different studies, including the Relaxation Rating Scale (RRS) which was collected in Amores et al. (2018) before and after the exposure, and in Lopes et al. (2022) just after exposure. Overall, five studies acquired some type of subjective measure only after the virtual experience (Hedblom et al., 2019; Song et al., 2019; Lopes et al., 2022; Shin et al., 2022; Zhao et al., 2022). Moreover, five studies used tasks to induce stress prior to exposure. In Zhao et al. (2022), participants were given a 3-min

TABLE 5 Summary of restorative effects reported in the reviewed studies.

Study	Restorative effects	Outcomes
Zhang et al. (2023)	Not measured	-
Shin et al. (2022)	Yes	Results of one-way ANOVA showed significant restorativeness/restoration across conditions for the ROS subscales 'Being Away' and 'Fascination' ($p < 0.05$)
Qi et al. (2022)	Yes	No significant effect on psychological restoration
Lopes et al. (2022)	Not measured	-
Takayama et al. (2022)	Yes	Psychological restorative effects were confirmed, with a significant decrease ($p < 0.01$) in "negative affect" (measured using PANAS) and a significant increase ($p < 0.01$) in the sense of restoration (measured using ROS) after the experience
Zhao et al. (2022)	Yes	In virtual forest conditions (with and without nature smell), ratings of perceived restoration and focus were significantly higher than the neutral condition ($p < 0.05$, Wilcoxon signed-rank test). In addition, there was a significant difference in restoration perception among the three conditions ($p < 0.05$, Friedman's test)
Abbott and Diaz-Artiles (2022)	Yes	Participants reported significantly lower STAI-6 scores after the audio-visual-olfactory than in the audio-visual condition ($p = 0.03$). Compared to the stressed state, PANAS Negative Affect ($p = 0.003$) and STAI-6 ($p = 0.001$) scores decreased after the audio-visual-olfactory condition. STAI-6 scores ($p = 0.013$) also decreased from baseline in audio-visual-olfactory condition
Schebella et al. (2020)	Yes	Low biodiversity natural environment was the most restorative during recovery from induced stress (TSST-IVE). Natural environments were more restorative than urban environments. Among the natural environments, moderate biodiversity immersive virtual environment was the least restorative
Putrino et al. (2020)	Not measured	-
Song et al. (2019)	Not measured	-
Hedblom et al. (2019)	Not measured	-
Sona et al. (2019)	Yes	The experience with nature view was perceived as more restorative (r = 39, $p < 0.01$) than the control group (no stimulus) and the lounge simulations (r = 0.22, $p < 0.05$)
Amores et al. (2018)	Not measured	-
Serrano et al. (2016)	Not measured	-

reading comprehension task similar to those given on a graduate standardized test. In Abbott and Diaz-Artiles (2022) and Schebella et al. (2020), the modified trier social stress test (TSST) was used. In Hedblom et al. (2019), mild electric shocks were used as a stress trigger. Finally, in Sona et al. (2019), a sequence of tasks was used to induce stress, including a single N-back task, a Stroop task, and an Attention Network Task.

3.6.2 Emotional restoration, mood, and perceived stress

The addition of olfactory stimuli in virtual nature experiences has resulted in inconsistent outcomes concerning effects on emotional restoration and positive/negative emotion. Table 5 shows a summary concerning the restorative effects mentioned in the studies. While some studies have reported an improvement in mood and stress reduction, others have reported no significant differences. For example, in Shin et al. (2022), the conditions where the participants looked out the window at nature showed greater restorative qualities than the absence of nature, but comparisons between the closed window condition (only view of nature) and the open window condition (sight, smell, and sounds of nature) showed no significant differences. Several participants did, however, report the open window condition to be more captivating. Results of one-way ANOVAs showed significant restorativeness/restoration across conditions for the ROS subscales 'Being Away' and 'Fascination' ($p < 0.05$).

In Qi et al. (2022), the audio-visual-olfactory stimuli led to an increased physiological restoration and overall perceived quality, whereas the audio-olfactory stimuli, despite having no significant effect on psychological restoration, showed an increase in perceived overall feelings of attraction to the landscape and a sense of overall harmony. For the audio-visual and audio-visual-olfactory conditions, no significant differences in psychological effects were found. Only for the auditory stimulus was the STAI-S value significantly lower than the control group ($p = 0.04$). In another study Zhao et al. (2022), in turn, after the two virtual forest conditions (with and without nature smell), ratings of perceived restoration and focus were significantly $p < 0.05$ higher than the neutral condition (i.e., post-hoc comparisons, using a Wilcoxon signed-rank test, audio-visual-olfactory, Z = 17.50, p = 0.000 and audio-visual Z = 13.0, p = 0.000). However, stress development was slower and recovery was greater in the forest without scent condition compared to the other conditions. In addition, Friedman's test showed a significant (p < 0.05) difference in restoration perception among the three conditions ($X^2(36)$ = 39.78, p = 0.000). Also, in Takayama et al. (2022) negative mood states (measured using POMS), significantly decreased (p < 0.01) after the experience (i.e., tension-anxiety, depression, anger-hostility, fatigue, and confusion). In addition, psychological restorative effects were confirmed, with a significant decrease (p < 0.01) in "negative affect" (measured using PANAS) and a significant increase (p < 0.01) in the sense of restoration (measured using ROS) after the experience.

Regarding negative emotions, in Abbott and Diaz-Artiles (2022), participants experienced a notable reduction in STAI-6 scores following the audio-visual-olfactory condition compared to the audio-visual condition (p = 0.03). Furthermore, when contrasted with their stressed state, there was a significant decrease in both PANAS Negative Affect (p = 0.003) and STAI-6 scores (p = 0.001) after the audio-visual-olfactory. Additionally, STAI-6 scores showed a significant decline from the baseline in the audio-visual-olfactory condition (p = 0.013). Results suggested that the addition of olfactory stimuli to the VR environment aided in reducing negative affect and state anxiety levels.

For positive emotions, significant improvements in relaxation were reported in Lopes et al. (2022); Amores et al. (2018). In Amores et al. (2018), the results showed that the multisensory VR experience was able to promote increased relaxation relative to the baseline condition, although not a significant difference. The findings corroborate previous studies that showed forest-related stimuli significantly increasing the participants' feelings of comfort and relaxation relative to a control condition (p < 0.05) Song et al. (2019). Similar findings were shown in Lopes et al. (2022) where greater relaxation was achieved as more senses were stimulated (p < 0.05). Moreover, the work in Sona et al. (2019) the correlation between the two multisensory environment experiences showed that nature views were perceived as more pleasant (r = 0.74, p < 0.01) and restorative (r = 39, p < 0.01) than the control group (no stimulus). Adding nature smells facilitated the recovery of personal resources (mood, fatigue, arousal) via greater scent pleasantness and fascination (r = 0.18, p < 0.10). Moreover, correlation analyses between experiences showed that the view was perceived as more pleasant (r = 0.53, p < 0.01) and the environment as more restorative (r = 0.22, p < 0.05) in the nature simulations than in the lounge simulations. In Serrano et al. (2016), the results showed that the VR experience was effective in inducing relaxation F(1,132) = 90.31, p < 0.001, where positive moods and the sense of presence increased. Moreover, a significant decrease in arousal (F(1,132) = 92.04, p < 0.001) was observed after all four VR experiences. However, no statistical differences were found between the four groups on emotions and sense of presence. In Hedblom et al. (2019), the perceived pleasantness, average over environments and sensory stimuli rated on a 1–100 scale, was significantly higher in the park environment (Mean = 69.21, SD = ±11.1) compared to both the forest (Mean = 62.7, SD = ±12.74; p = 0.01) and the urban area (p < 0.001). Perceived pleasantness was also higher for the forest relative to the urban area (Mean = 37.19, SD = ±14.22; p < 0.001). There were significant differences in the ratings of perceived pleasantness among the three environments, as indicated by the sensory stimuli (t = 90.01; p < 0.001; pairwise comparisons).

Regarding perceived stress, Schebella et al. (2020) showed that a multisensory experience (visual, auditory, and olfactory) was associated with better recovery in all measures of wellbeing relative to a visual-only experience. Median anxiety recovery scores were significantly greater in the audio-visual-olfactory high biodiversity environment (33.00) than in the visual-only (17.50) using a Mann–Whitney test (U = 90.50, z = 1.971, p = 0.047). When compared to the virtual urban environment, stress recovery was most effective in a low-biodiversity environment (p < 0.05). In Putrino et al. (2020), a greater reduction in perceived stress after the multisensory immersive experience was reported (p < 0.001), where the level of stress had an average reduction of 59.6% in the self-reported ratings. Similarly, in Hedblom et al. (2019), the park and forest conditions resulted in significant stress reduction, whereas the urban area condition did not.

3.7 Outcome assessment (physiological)

In total, nine articles performed some type of physiological measurement and assessment (Amores et al., 2018; Hedblom et al., 2019; Song et al., 2019; Schebella et al., 2020; Lopes et al., 2022; Qi et al., 2022; Takayama et al., 2022; Zhao et al., 2022; Zhang et al., 2023). Only three of them, however, measured physiological stress through stress induction (Hedblom et al., 2019; Schebella et al., 2020; Zhao et al., 2022). In particular, five studies measured cardiovascular data (Song et al., 2019; Schebella et al., 2020; Lopes et al., 2022; Takayama et al., 2022; Zhao et al., 2022), two measured blood pressure and pulse Zhang et al. (2023); Takayama et al. (2022), one measured salivary amylase activity (Takayama et al., 2022), four assessed electrodermal activity (EDA) (Hedblom et al., 2019; Lopes et al., 2022; Qi et al., 2022; Zhang et al., 2023), one measured skin temperature (Qi et al., 2022), one measured oxy-hemoglobin concentration in left and right prefrontal cortices as an indicator of brain activity using near-infrared spectroscopy (Song et al., 2019), and three used electroencephalography (EEG) to measure neural activity (Amores et al., 2018; Qi et al., 2022; Zhang et al., 2023). More details about each modality are presented next.

3.7.1 Blood pressure and pulse

The study described in Zhang et al. (2023) investigated the effects of olfactory and olfactory-visual stimulation on blood pressure and pulse. During the stimulation, it was observed that systolic blood pressure (SBP) values remained relatively unchanged. However, diastolic blood pressure (DBP) values exhibited a significant increase (ΔDBP = 4.37 ± 1.69 mmHg, p < 0.05). Additionally, the pulse pressure difference (PP) values demonstrated a notable decrease during both stimulations (ΔPP = −4.56 ± 1.24 mmHg, p < 0.05). Furthermore, during olfactory stimulation, pulse values also showed a significant decrease (ΔP = −2.34 ± 1.16 bmp, p < 0.05). In contrast, visual stimulation did not lead to significant changes in SBP, DBP, or PP. These findings suggest that the physiological effects were greater when the olfactory system was stimulated. Conversely, in Takayama et al. (2022) no significant differences in DBP, SBP, or pulse rate were seen before and after experiencing the digital forest bathing environment.

3.7.2 Skin temperature

Only one study looked at skin temperature (ST) changes (Qi et al., 2022). While the results did not show significance, the restorative tendency for auditory stimuli was greater than in the control group.

3.7.3 Salivary amylase

Similarly, only one study measured salivary amylase (Takayama et al., 2022). No significant effect was observed when comparing the data before and after the multisensory digital forest experience.

3.7.4 Near-infrared spectroscopy (NIRS)

The study described in Song et al. (2019) demonstrated that the combined visual and olfactory stimuli yielded significantly reduced oxygenated hemoglobin (oxy-Hb) concentrations in both the left (control, -0.08 ± 0.10 μM; visual-olfactory, -0.48 ± 0.09 μM; $p < 0.05$) and right (control, 0.02 ± 0.10 μM; visual-olfactory, -0.46 ± 0.08 μM; $p < 0.05$) prefrontal cortices, compared to the control condition. Additionally, when exposed to the olfactory stimulus alone, a significant decrease in oxy-Hb concentration was observed in the right prefrontal cortex compared to the control condition (olfactory, -0.32 ± 0.12 μM). This decrease in oxy-Hb concentration aligns with previous literature suggesting its association with physiological calming (Hoshi et al., 2011). Overall, these findings suggest greater relaxation effects resulting from the combined visual and olfactory stimuli.

3.7.5 Cardiovascular data

Regarding the cardiovascular system, there were five studies that show results related to relaxation and stress reduction in multisensory experience (Song et al., 2019; Schebella et al., 2020; Lopes et al., 2022; Takayama et al., 2022; Zhao et al., 2022). In Lopes et al. (2022), despite not showing a statistically significant difference, the mean of the high frequency (HF) component of the electrocardiogram (ECG) signal (across all participants) for the multisensory condition was higher compared to the audiovisual-only condition. These findings are corroborated by other studies that showed increases in HF during deep relaxation situations, such as meditation, or a decrease in HF during stressful situations. In addition, the standard deviation of the absolute first difference of the ECG feature showed a significant negative correlation ($r = -0.46$, $p < 0.05$) with the subjective relaxation rating for the multisensory condition, thus suggesting that the users felt more relaxed in the multisensory experience. Furthermore, the results also showed a decrease in the maximum blood volume pulse (BVP) signal between the audio-visual and multisensory (audio-visual-olfactory-haptic) conditions, suggesting greater relaxation potential in the latter condition (Parent et al., 2020).

In Takayama et al. (2022), the heart rate significantly decreased ($p < 0.01$) and HF was significantly higher ($p = 0.014$) during the exposure to multisensory forest bathing compared with that during the resting state. On the other hand, the study in Zhao et al. (2022) used heart rate variability (HRV) to compare three conditions during stress-inducing and recovery tasks. They found significant differences ($p < 0.05$) in HRV among these conditions. Specifically, the audio-visual condition showed a notably higher HRV than the neutral condition across all metrics. Additionally, HRV in the audio-visual condition was generally higher than in the audio-visual-olfactory condition. The results suggest that the nature experience without scent was the most effective in promoting relaxation.

Regarding the comparison between urban and natural environments, in Schebella et al. (2020), results showed that there were no significant differences in recovery from stress induction in terms of heart rate and HRV. However, regarding the stimulus in the experience, the multisensory experience showed that the recovery from stress induction relative to a visual-only condition was higher in terms of reduced heart rate and HRV. Moreover, the greatest recovery from stress induction based on median HR recovery scores ($X^2(2) = 9.234$, $p = 0.007$) was found in the low biodiversity condition, relative to the moderate biodiversity natural environment. Lastly, in Song et al. (2019), findings derived from HRV (i.e., $\ln(LF/HF)$) showed that only the visual stimulus resulted in significantly decreased sympathetic nervous activity compared to the control condition (control, -0.26 ± 0.17; visual, -0.67 ± 0.17; $p < 0.05$), which indicates a decrease in stress. When comparing the four conditions (control, visual, olfactory, and visual-olfactory) there was no significant difference in heart rate.

3.7.6 Electrodermal activity

Four studies reported changes in electrodermal activity (EDA) when including multisensory experiences. In Zhang et al. (2023), in the visual condition, the amplitudes of skin conductance (SC) ($\Delta SC = 0.19 \pm 0.01$ $\mu\Omega$, $p < 0.05$) increased significantly relative to the control group. In addition, SC values significantly increased under the olfactory–visual stimulus method ($\Delta SC = 0.45 \pm 0.34$ $\mu\Omega$, $p < 0.05$), and this increase was significantly higher than that of the olfactory-only condition. These findings may indicate that the effect of smelling and seeing garden plants provides more excitement than just smelling or seeing. On the other hand, the work in Qi et al. (2022) showed that in terms of the physiological restoration, the skin conductance level (SCL) value revealed a negative effect in the audio-olfactory stimulation, only the audio stimulus resulted in higher levels of restoration than the control group, illustrated by the SCL ($p = 0.04$).

According to the findings in Lopes et al. (2022), the participants in the multisensory condition exhibited a lower average of the low-frequency component in the EDA signal compared to the audio-visual condition. An elevation in the low-frequency component of EDA has been linked to stress (Posada-Quintero et al., 2016). Moreover, a Pearson correlation analysis revealed significant correlations ($p < 0.05$) between EDA features and relaxation ratings. Notably, the mean of the negative first difference of the EDA signal showed a correlation of $r = 0.42$, and the standard deviation of the EDA signal had a correlation of $r = -0.43$. Lastly, in the study by Hedblom et al. (2019), a greater decrease in EDA was observed in natural (park) environments compared to urban environments, with a significant difference ($\beta = 2.02$, ($t(2471) = 2.45$; $p < 0.02$)). A similar trend, though not statistically significant, was also noted between park and forest environments ($\beta = 0.56$, ($t(2471) = 0.67$, $p = 0.25$)). The study used a regression model to explore the relationship between perceived environmental pleasantness and SCL values during stress and recovery periods. It was found that only odor pleasantness significantly predicted SCL during both periods (stress period: $\beta = -0.164$; $p = 0.04$; recovery period: $\beta = -0.188$; $p = 0.03$), with auditory pleasantness showing marginal significance in the recovery period ($\beta = -0.45$; $p = 0.05$).

3.7.7 Electroencephalography

Most studies measuring electroencephalographic activity focused on alpha waves, which represent a state of calm and feelings of quietness and relaxation. Two studies, in addition to alpha waves, also showed results related to beta waves, which are related to effortful thinking and active attention. In Zhang et al. (2023), there was a significant increase in alpha and beta wave power during visual and combined olfactory-visual stimulation compared to before the stimulation. Specifically, alpha waves increased from $13.90 \pm 7.19\ \mu V$ to $20.10 \pm 9.45\ \mu V$ ($p < 0.001$) in the visual condition and from $16.03 \pm 5.03\ \mu V$ to $18.31 \pm 6.77\ \mu V$ ($p < 0.05$) in the olfactory-visual condition. Beta waves also rose from $8.27 \pm 5.09\ \mu V$ to $13.78 \pm 6.79\ \mu V$ ($p < 0.001$) in the visual condition and from $10.12 \pm 4.35\ \mu V$ to $11.52 \pm 4.87\ \mu V$ ($p < 0.05$) in the olfactory-visual condition. No significant changes were noted with olfactory stimulation alone. However, when compared to a control group, all three conditions showed a significant increase in both alpha and beta wave powers.

In Qi et al. (2022), audio-visual-olfactory stimuli led to greater restoration, but only for beta wave power (compared with the only-audio condition). As for the alpha wave power, correlations were seen with a lifting effect in the audio-visual condition and a negative effect in the audio-olfactory condition ($p = 0.00$) with a relatively equal mean difference when compared to the audio-only condition. Combining audio (birdsong) with olfactory stimuli from environments such as rose gardens and pine forests led to a significant decrease in α power ($p \leq 0.01$). An osmanthus garden also notably lowered α power ($p = 0.00$), indicating that certain plant landscapes may induce negative physical arousal. Regarding β band power, adding visual and visual-olfactory stimuli to audio-only (birdsong) scenarios generally improved restoration ($p = 0.00$). However, in lawn settings, the addition of visual-olfactory stimuli had a variable impact on β values ($p = 0.00$). The work in Amores et al. (2018) also investigated changes in theta wave, which can be observed during meditation and drowsiness. A relaxation metric based on the Renyi entropy of different EEG frequency bands was proposed and showed that the relaxation score increased significantly ($p < 0.05$) between the audio-visual-olfactory experience and the control condition (no stimulus).

3.8 Limitations and future study recommendations

Of the 154 studies looking at some experiments with immersive nature environments involving VR, only 14 covered audio-visual-olfactory aspects, suggesting this is an emerging topic with room for innovation and development. In the subsections to follow, several limitations are addressed and recommendations for future studies are provided.

3.8.1 Population

Several studies have faced limitations due to demographic constraints (e.g. (Sona et al., 2019; Qi et al., 2022; Shin et al., 2022; Zhang et al., 2023)). These studies often do not account for the full spectrum of diversity in age, gender, ethnicity, or socioeconomic status. This lack of diversity can hinder the generalizability of the findings, potentially leading to conclusions that may not apply broadly across different demographic groups. For example, the majority of the participants in the studies were comprised of university students, which could not fully represent the target population for multisensory immersive experience interventions. Moreover, very few studies had balanced gender representation in the participant pool. Some previous studies have reported increased chances of motion sickness (known as cybersickness) for females relative to males (e.g. (Kelly et al., 2023)). As such, future studies should strive to include a more diverse sample, including from a patient population, to enhance the generalizability of the findings.

Moreover, the reliability of the reported findings is often compromised by limited sample sizes (e.g. (Amores et al., 2018; Song et al., 2019; Schebella et al., 2020; Abbott and Diaz-Artiles, 2022; Lopes et al., 2022; Takayama et al., 2022; Zhao et al., 2022)). Small sample sizes can result in poor statistical power, making it challenging to detect true effects or differences, and may lead to results that are not replicable in larger, more diverse samples. Researchers should aim to increase sample sizes in future studies. Larger sample sizes would improve the statistical power and the robustness of the findings, contributing to more reliable and valid research outcomes.

Another significant limitation, as noted by Song et al. (2019), is the lack of studies with populations with heightened daily stress (e.g., first responders). Overlooking high-stress groups can lead to a gap in understanding their specific needs and responses. Future studies should concentrate on these populations, as targeted research can provide important insights into stress management and resilience, aiding in the development of effective interventions and therapies for those heavily impacted by stress.

Lastly, cultural background plays a pivotal role in shaping an individual's preference for specific natural odors, deeply influencing the design and customization of the olfactory element in a virtual experience. For example, the Japanese practice of Shinrin-Yoku highlights the cultural value placed on the immersive experience of forest scents, such as those from pines, cedars, and spruces. Furthermore, the type of vegetation and biodiversity characteristic of a region can significantly influence the natural odors that individuals find comforting. For instance, individuals from regions rich in coniferous forests may have a preference for the scents of pine or fir, while those from tropical areas might be drawn to the fragrances of flora like banyan or kauri trees. Acknowledging these cultural and regional differences is crucial in creating more inclusive and personalized virtual reality experiences. By offering a wide selection of natural scents, from the refreshing aroma of a dense forest to the salty breeze of a beach, virtual environments can cater to a global audience. This approach not only enhances the immersive quality of virtual experiences but also fosters a deeper connection between users and the virtual natural environments they choose to explore, based on their personal experiences with nature.

Further research should explore the impact of olfactory preferences on overall relaxation potential.

3.8.2 Lack of stimuli comparisons

Studies, such as those by (Song et al., 2019; Zhang et al., 2023), focused predominantly on visual and olfactory stimuli, while works, such as (Amores et al., 2018; Putrino et al., 2020; Takayama et al., 2022), emphasized multisensory experiences. The absence of a comprehensive integration strategy and comparison of the three sensory inputs can lead to a fragmented understanding of their synergistic potential and impact. Future research should strive to integrate and compare audio, visual, and olfactory stimuli in a cohesive manner. Studies could explore how these stimuli interact and influence mental health outcomes when used together, as opposed to in isolation or in paired combinations. This integrated approach can provide deeper insights into the multisensory experience, particularly in how olfactory stimuli complement and enhance visual and auditory experiences.

3.8.3 Lack of complementary measures

A critical limitation noted in studies, such as that by Zhang et al. (2023), is the exclusive focus on physiological indicators, neglecting psychological aspects. Conversely, research by Shin et al. (2022); Abbott and Diaz-Artiles (2022); Putrino et al. (2020); Sona et al. (2019); Serrano et al. (2016) have primarily relied on subjective analyses. This one-dimensional approach can result in an incomplete understanding of the study subject, as it fails to capture the holistic impact of the interventions or phenomena being studied. Future studies should aim to incorporate both objective (physiological) and subjective (psychological) measures. This dual approach would provide a more comprehensive understanding of the effects being studied. For instance, while physiological data can offer concrete evidence of bodily responses, psychological data can provide insights into personal experiences and perceptions. The integration of both types of data can lead to a more nuanced and complete understanding of the research findings.

In fact, several studies relied on a single objective measurement (e.g. (Amores et al., 2018; Hedblom et al., 2019; Zhao et al., 2022)), thus may have missed some important interactions between the central and nervous systems, which have been linked to different emotional states and behaviors. In turn, the work by Qi et al. (2022) relied on a single subjective measurement, which can result in a narrow understanding of participant experiences. Additionally, the studies by Lopes et al. (2022); Putrino et al. (2020); Amores et al. (2018) relied on single-item self-reports. Multi-item scales and the incorporation of a wider array of subjective tools should be used in future studies to capture a more comprehensive view of participant experiences and perspectives.

3.8.4 Smell perception

3.8.4.1 Narrow focus on odor elements in olfactory environments

Research, such as in Zhang et al. (2023), focused mainly on odor elements in garden green spaces, overlooking the broader spectrum of sensory experiences in olfactory environments. This limited perspective may not fully capture how various sensory inputs together enhance environmental quality and health benefits. Future research should broaden its scope to include how visual, auditory (and tactile) elements interact with olfactory experiences, offering a more comprehensive understanding of olfactory environments and their role in wellbeing and environmental enhancement.

3.8.4.2 Limited strategies in stimulating the sense of smell

Two studies did not compare the multisensory condition with a conventional audio-visual condition, thus making it difficult to fully characterize the impact of including olfaction and its role in anxiety/stress reduction (Amores et al., 2018; Takayama et al., 2022). It is recommended that future studies should include appropriate control conditions to allow direct comparisons of outcomes from conventional to multisensory interventions.

Moreover, the study by Zhao et al. (2022) highlighted a limitation in using a single method for olfactory stimulation (using the Aroma Shooter device), leading to uncertain conclusions about other techniques, such as other diffusion devices, incenses, or the use of natural plant aromas. Despite the fact that only this particular study acknowledged such a limitation, it is important to note that all the studies included in this review uniformly employed a singular method for stimulating the olfactory sense. This limits the understanding of the impact of different smell stimulation methods on stress recovery and health. Future studies should explore diverse smell stimulation methods, including varying scent types, intensities, and combinations, possibly alongside other senses. Comparing these strategies can offer insights into their effectiveness, particularly for stress relief.

3.8.4.3 Interactive olfactory technology

In acknowledging the significance of individual preferences in VR experiences, particularly within the olfactory dimension, it is important to emphasize that personalization and user interaction in virtual olfactory environments also have great importance in the overall experience. The ability for users to tailor their sensory experiences to their preferences can enhance the immersion and realism of VR.

Technologies such as the OVR ION Technology (2017) wearable scent diffusion device allow for up to nine different scents to be diffused, thus offering users a broad spectrum of olfactory experiences. The technology not only allows for the continuous diffusion of "background" scents but also enables interactive experiences where the emission of scents is tied to user actions and specific objects within the virtual environment. For instance, interacting with a virtual rose can trigger the emission of rose petal smells, thus closely mimicking real-world experiences.

Moreover, the Olorama Scent Generator (OSG) Olorama (2013) exemplifies another way for users to interact with virtual objects with up to 10 different smells. This device adapts the olfactory output based on the virtual scene, enhancing the immersive quality of the VR experience. Similarly, the SENSIKS SENSIKS (2017) sensory reality pod, while not portable, supports six distinct scents and modifies scent emissions in response to the virtual content, demonstrating the versatility and adaptability of current olfactory technology.

Additionally, with microcontrollers such as Arduino, developers can design their own VR-integrated smell devices, further democratizing the field and opening up new possibilities for personalized sensory experiences. Examples include the use of computer-controlled olfactometers Lundström et al. (2010), Essence Amores and Maes (2017), and olfactory wearables Amores Fernandez et al. (2023), highlighting the field of virtual olfactory experiences. These examples not only offer a wide range of scents for user selection but also enable dynamic and personalized VR experiences that cater to the nuanced preferences of users. Future studies should consider allowing the user to validate and calibrate the olfactory elements based on their own preferences (e.g., adjust smell "gains" based on proximity to the nose).

3.8.5 Individualized analyses

Studies, such as (Song et al., 2019; Zhang et al., 2023), were the only ones to analyze the stimuli and their effects at the individual level. As smell is very subjective (pleasant for some, unpleasant for others), performing analyses at the group level may average out some interesting individualized outcomes. Future research should highlight both individual and group analyses to provide deeper insights into how each stimulus uniquely contributes to the overall outcome, essential in sensory and psychological research.

3.8.6 Virtual environment choices

Most studies offered a limited range of nature scenes, often focusing on a single type of environment (e.g., a forest). This limited range fails to consider the diverse preferences and responses individuals might have to different natural settings. Only a few works (e.g. (Serrano et al., 2016; Hedblom et al., 2019; Putrino et al., 2020; Qi et al., 2022)) offered different types of nature scenes. Future research should expand the range of environmental options presented to participants. Offering a diverse array of nature scenes, each with distinct characteristics (e.g., beach, mountain, urban green space), can cater to varied individual preferences and potentially yield richer data on environment-person interactions.

Personalization can play a crucial role in how individuals interact with and respond to different settings, impacting their psychological and physiological wellbeing. For example, Reid et al. (2015) demonstrated that odors can evoke emotional and nostalgic responses, enhancing the immersive quality of digital experiences. Incorporating options for personalizing the environmental experience can be a significant step forward in future research. Allowing participants to choose or even modify their environment according to their preferences can provide insights into how personalization affects their experience and response.

Moreover, as highlighted by Lopes et al. (2022), virtual experiments are often short in duration, in the order of a few minutes. Such short durations may limit the effectiveness of heart rate variability, which can often rely on tens of minutes. To capture more detailed biological features, extending experiment times to at least 10 min is recommended for more reliable and comprehensive physiological assessments.

3.8.7 Modality mismatch

Studies such as Amores et al. (2018) and Serrano et al. (2016) highlight a crucial limitation: the mismatch of sensory modalities. For instance, using lavender essential oil in a beach scenario can create sensory dissonance. This inconsistency can disrupt the coherence of the user experience, potentially diminishing the intended effect of the environment, whether it be for relaxation, stress reduction, or immersion. Future research should focus on creating sensory congruence in multisensory environments. This means ensuring that all sensory inputs are harmoniously aligned to reinforce each other.

3.8.8 Limited objective measurements

Of the studies analyzed, only nine utilized objective measurements to quantitatively assess the effects of sensory stimuli. Objective measurement via wearables, for example, may allow for close to real-time monitoring of user affective states, as well as the development of biomarkers that could be used to quantitatively monitor intervention outcomes in the long term. Wearables have been shown to be a useful ally for stress management interventions (e.g. (Smith E. N. et al., 2020; Gomes et al., 2023)), thus should be considered in future studies. Identifying the most sensitive and informative wearable devices or measurements will be crucial for the understanding of the role of olfactory stimuli in digital nature bathing.

Moreover, only four of the nine studies relied on monitoring neural data while the user was immersed in the virtual environment (Amores et al., 2018; Song et al., 2019; Qi et al., 2022; Zhang et al., 2023). Unlike other wearable devices that are typically placed on wrists, chests, or arms, the collection of neural data, while the user is wearing an HMD, may be challenging. There are recent innovations in sensor-embedded HMDs that may help overcome this limitation (e.g. (Cassani et al., 2020; Bernal et al., 2022; Moinnereau et al., 2022)). Physiological measures derived from EEG can provide new insights into the immersive experience and its mental health impact. For instance, the works by Abbasi et al. (2019); Wu et al. (2023) showed the use of EEG to study emotional responses to olfactory stimuli. Future studies should consider the use of such devices to allow for real-time monitoring of mental/cognitive states, as well as the development of new neuromarkers of VR nature exposure outcomes.

3.8.9 Beyond audio-visual-olfactory

While this review did not specifically focus on multisensory experiences relying on only haptic/tactile/somatosensory stimuli, three of the fourteen studies did include audio-visual-olfactory-tactile stimuli. Recent studies are showing that as more senses are stimulated, a greater sense of presence, immersion, and engagement can be achieved (De Jesus Jr et al., 2022; Gougeh et al., 2022), as well as improved neural plasticity (Amini Gougeh and Falk, 2023). Vibroacoustic therapy has shown to be useful for stress management (Boyd-Brewer, 2003). Additionally, the effects of thermal perception have been shown to have restorative benefits Lyu et al. (2022); Song et al. (2024). Future studies should explore the inclusion of tactile/somatosensory stimuli to further enhance the relaxation potential of the intervention.

3.8.10 Quality analyses

Lastly, we attempted to quantify the quality of the reviewed studies via different quality checklists. While the majority was rated as moderate to high quality, two were deemed as low quality, which could have introduced biases and affected the overall reliability of the findings reported herein. Future works should aim to follow quality guidelines in (Tufanaru et al., 2020) to ensure outcomes are reliable.

3.9 Recommendations for future research

Of the 14 studies reviewed, those incorporating olfactory stimuli alongside visual and/or auditory elements showed a marked improvement in stress reduction and relaxation. Here, we base our recommendations on those with a greater number of participants, which are likely to have increased statistical power and can have outcomes better reproduced in future studies. In the examined studies, this corresponded to experiments with the number of participants greater than 50. The study by Zhang et al. (2023), for example, demonstrated that combining visual and olfactory senses significantly enhanced biomarkers of relaxation, with a sample of 95 participants and a statistical significance of $p < 0.05$. The study showed increases in DBP, SC amplitudes, alpha, and beta brainwaves, while PP decreased. They utilized panoramic photos of Osmanthus trees and the natural scent of Osmanthus flowers, suggesting that smells from real objects might be just as effective in inducing relaxation as the ones based on essential oils, as in other studies (e.g., Lopes et al., 2022; Takayama et al., 2022).

Interestingly, the work by Takayama et al. (2022) relied on projected nature scenes, as opposed to immersing the user via an HMD. This highlights the importance of the olfactory channel, regardless of the visual modality used to immerse the user. Future works should explore more closely the differences between audio-visual-olfactory immersion using photos, projected videos, and immersive videos presented via HMDs to gauge the benefits of improved presence on overall relaxation. This aspect was not compared in any of the investigated studies.

Moreover, the works by Schebella et al. (2020) and Hedblom et al. (2019), with 52 and 154 participants respectively, found that nature settings even with low biodiversity, such as an Eucalyptus forest or a park, were significantly more effective in eliciting positive emotions, such as happiness and pleasantness, compared to urban environments ($p < 0.05$). These studies also measured physiological responses through EDA and HR. Key to these studies was also the synchronized presentation of olfactory stimuli with the visual environment and, when applicable, auditory elements, such as birdsong and nature sounds. Immersion of all senses in a natural setting is at the heart of Shinrin-yoku (forest bathing) principles, thus future works should aim to stimulate as many senses as possible while simulating a nature setting.

4 Conclusion

This systematic review has presented a comprehensive synthesis of the psychological and physiological effects of multisensory (audio-visual-olfactory) virtual nature exposure on mental health, as well as existing systems. A total of 14 studies were examined, involving virtual forests, beaches, and parks, where corresponding odors were utilized in the multisensory conditions. The majority of the studies reported enhanced restoration outcomes following exposure to multisensory conditions. We conclude by discussing several limitations and propose some recommendations for future studies. The reviewed literature suggests that, overall, multisensory immersive digital nature exposure can be an intervention that holds promise for mental health and wellbeing.

Data availability statement

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

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

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

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2024.1252539/full#supplementary-material

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