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Effects of multisensory virtual reality nature on affect, presence, and restorativeness

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Abstract

Virtual reality (VR) can provide access to restorative environments and sensory stimulation for individuals in isolated, confined, and extreme environments. We developed a nature-based VR intervention featuring three scenes (Garden, Forest, Beach) and examined the effects of multisensory augmentation with location-based olfactory, wind, and thermal stimuli (VR + OWT). Over a two-week period, fifty-one participants were assigned to a no-intervention control, standard audiovisual VR, or augmented VR (VR + OWT) condition. Data collection included weekly assessments of affect, stress, and cognitive performance; post-VR measures of affect, presence, and perceived restorativeness; and open-ended feedback. Both VR and VR + OWT groups produced immediate and sustained reductions in negative affect with no sustained systematic benefits on cognitive performance. The addition of olfactory, wind, and thermal stimuli enhanced presence for some scenes; however, feedback indicated that sensory mismatches and stimulus intensity occasionally detracted from the experience and may have contributed to lower coherence ratings in the VR + OWT group. In contrast, the perceived restorativeness of the VR environment was driven primarily by scene content (Garden vs Forest vs Beach) rather than the level of sensory stimulation. These findings support the potential of virtual nature to promote well-being and underscore the importance of coherence across sensory modalities for multisensory augmentation.

Introduction

Living and working in isolated, confined, and extreme (ICE) environments, such as long-duration spaceflight, extended ocean voyages, and polar expeditions, are psychologically challenging and increases the risk of adverse behavioral health and cognitive conditions [1]. Depression, anxiety, withdrawal, interpersonal conflicts, and sleep disorders have been observed in astronauts and cosmonauts [2–4] and may impair performance and threaten mission success. Traditional psychological countermeasures, such as private conferences and care packages [5], rely on proximity to Earth and are unlikely to remain feasible for future exploration missions beyond low Earth orbit particularly for longer communication delays [6].

Exposure to natural environments reliably promotes well-being. Stress Recovery Theory [7, 8] and Attention Restoration Theory [9] propose that natural settings provide uniquely restorative settings supporting affective regulation, psychophysiological recovery, and cognitive restoration, with demonstrated benefits for stress, anxiety, mood, and attention [10–12]. Although ICE inhabitants lack access to real nature, virtual reality (VR) offers a promising means of delivering nature-based countermeasures in environments where direct exposure is impractical [13].

While virtual nature can confer benefits comparable to real nature under certain conditions [14], its effects are often attenuated relative to physical exposure [15, 16]. One likely contributor is limited sensory immersion: most VR applications rely primarily on audiovisual input. The term *immersion* refers to the objective sensory affordances of a system, whereas *presence* reflects the subjective sense of

"being there" [17]. Greater *immersion* supports stronger *presence*, which is critical for effective virtual experiences [18–20].

Multisensory VR remains underexplored, particularly the integration of olfactory and haptic cues. Previous work suggests that incorporating multiple sensory modalities can enhance presence [21–23] and facilitate relaxation and psychophysiological recovery [24], with multimodal stimulation producing synergistic effects relative to unimodal input [25, 26]. However, existing multisensory implementations typically employ static stimuli (e.g., constant temperature or scent), which may reduce believability and lead to sensory mismatches or neural adaptation [27]. In contrast, dynamic stimuli could enhance the virtual experience by increasing coherence across sensory modalities, sustaining perceptual engagement, and fostering greater presence. Further, dynamic stimuli add a layer of interaction between the user and the environment, which may further improve presence [18, 28].

We evaluate the effects of varying levels of sensory stimuli in a VR nature intervention, comparing: a control condition, a standard audiovisual VR condition (VR), and a multisensory condition with VR that incorporated olfactory, wind, and thermal stimuli (VR + OWT). We examine immediate effects on affect, presence, and perceived restorativeness, as well as sustained changes in affect and stress and cognitive performance over a two-week intervention period. Together, these findings aim to characterize the influence of multisensory augmentation on both the short- and longer-term restorative potential of virtual nature.

Results

Immediate Effects of VR Intervention

PANAS: Positive Affect and Negative Affect Schedule (PANAS) scores by Condition (VR, VR+OWT) and Scene (T1, and Post-VR for the Garden, Forest, and Beach) are shown in Figure 1. Positive Affect (PA) scores were not significantly different between Conditions (0.37, 95% CI [−3.93, 4.64], p=0.87), and there was no significant effect of Scene [F(3,91.0)=1.91, p=0.13] or Condition x Scene [F(3,91.0)=1.35, p=0.26].

Similarly, Negative Affect (NA) scores were not significantly different between Conditions (−0.04, 95% CI [−3.32, 3.23], p=0.98) with no Condition x Scene interaction [Wald $\chi^2(3)=1.08$, p=0.78]. However, there was a significant effect of Scene [Wald $\chi^2(3)=23.53$, p<0.001]. Main effects contrasts, averaged over Condition, revealed that NA significantly decreased from T1 (baseline) to post-VR for the Garden (−3.67, 95% CI [−5.60, −1.73], p=0.004), Forest (−3.79, 95% CI [−5.65, −1.94], p<0.001), and Beach (−3.86, 95% CI [−5.73, −1.98], p<0.001). NA did not significantly differ between the three VR scenes (Garden, Forest, Beach), averaged across groups (all p > 0.9).

Simple effects contrasts revealed that compared to T1 (baseline), NA tended to decrease for the VR group in all scenes, but this was only significant in the Forest (−3.56, 95% CI [−6.18, −0.94], p=0.019) and Beach (−3.82, 95% CI [−6.50, −1.14], p=0.016) and not the Garden (−2.75, 95% CI [−5.55, 0.05], p=0.11).

Additionally, for the VR+OWT group, NA decreased significantly from T1 to post-VR for all scenes (Garden (−4.59, 95% CI [−7.26, −1.91], p=0.009), Forest (−4.03, 95% CI [−6.65, −1.41, p=0.014), and Beach (−3.90, 95% CI [−6.52, −1.27], p=0.014)).

IPQ: iGroup Presence Questionnaire (IPQ) subscales and total presence scores by Condition (VR, VR+OWT) and Scene (Post-VR for the Garden, Forest, Beach) are shown in Figure 2. IPQ Experienced Realism scores were not significantly different by Condition (0.34, 95% CI [−0.23, 0.90], p=0.23), and there was no significant effect of Scene [F(2,59.6)=1.33, p=0.27] and weak evidence for an interaction between Condition x Scene [F(2,59.6)=2.90, p=0.063].

IPQ General Presence was significantly higher in the VR+OWT group than the VR group (0.53, 95% CI [0.04, 1.07], p=0.032). There was no significant effect of Scene [Wald $\chi^2(2)=3.18$, p=0.2] or Condition x Scene [Wald $\chi^2(2)=2.25$, p=0.3]. Simple effects contrasts showed that differences between groups were most pronounced in the Garden (p=0.03), while other scenes showed similar trends that did not reach significance (both p>0.19).

IPQ Involvement was significantly higher in the VR+OWT group than the VR group (0.64, 95% CI [0.07, 1.21], p=0.03). There was a significant effect of Scene [F(2,60.1)=9.08, p<0.001] and a significant interaction between Condition x Scene [F(2,60.1)=4.03, p=0.02]. Simple effects contrasts showed that differences between groups was significant only for the Garden scene (1.24, 95% CI [0.52, 1.96], p=0.003) and not the Forest (p=0.27) or Beach (p=0.53). Furthermore, Involvement for the VR group was significantly higher in the Beach than the Garden (1.23, 95% CI [0.69, 1.78], p < 0.001) and Forest (0.74, 95% CI [0.22, 1.25], p=0.017).

IPQ Spatial Presence across all scenes tended to be higher for the VR+OWT group than the VR group (0.46, 95% CI [−0.004, 0.92]), though not statistically significant (p=0.052). There was no significant effect of Scene [F(2,60.0)=1.89, p=0.16] or Condition x Scene [F(2, 60.0)=0.80, p=0.5].

Finally, IPQ Total Presence was significantly higher for the VR+OWT group than the VR group (0.48, 95% CI [0.07, 0.89], p=0.02), and there was a significant effect of Scene [F(2, 60.0)=6.33, p=0.003] with weak evidence of a Condition x Scene interaction [F(2, 60.0)=2.88, p=0.06]. Averaged across Condition, Total Presence in the Beach was significantly higher than the Garden (0.36, 95% CI [0.16, 0.57], p=0.003) and Forest (0.23, 95% CI [0.03, 0.43], p=0.036). Simple effects contrasts showed that, for the VR group only, Total Presence was significantly higher in the Beach than the Garden (0.60, 95% CI [0.30, 0.91], p=0.001) and the Forest (0.40, 95% CI [0.12, 0.69], p=0.02). Further, Total Presence was significantly higher for the VR+OWT group than the VR group in the Garden (0.69, 95% CI [0.21, 1.16], p=0.02) and Forest (0.55, 95% CI [0.09, 1.01], p=0.03), but not the Beach (0.21, 95% CI [−0.26, 0.67], p=0.38).

PRS: Perceived Restorativeness Scale (PRS) subscales and Total Restorativeness scores by Condition (VR, VR+OWT) and Scene (Garden, Forest, Beach) are shown in Figure 3. The environments were generally perceived as restorative, with mean scores above the midpoint (3 on a 0−6 scale) for all PRS subscales. PRS Being Away did not significantly differ by Condition (0.58, 95% CI [−0.14, 1.30], p=0.11),

and there was no significant effect of Scene [F(2,60.0)=2.39, p=0.10] or Condition x Scene [F(2,60.0)=0.48, p=0.62].

PRS Coherence for the VR+OWT group showed a small, non-significant trend to be lower than the VR group (−0.30, 95% CI [−0.81, 0.21], p=0.24). There was a significant effect of Scene [F(2,59.6)=3.62, p=0.03] and no Condition x Scene interaction [F(2,60.0)=0.80, p=0.46]. Averaged over Condition, Coherence was significantly higher in the Garden than the Forest (−0.29, 95% CI [−0.54, −0.04], p=0.03) and the Beach (−0.30, 95% CI [−0.54, −0.05], p=0.03). Simple effects contrasts did not reveal any significant differences between VR scenes for either the VR group or VR+OWT group (all p >0.16).

PRS Compatibility did not differ by Condition (0.18, 95% CI [−0.52, 0.88], p=0.60), and there was no significant effect Scene [F(2,60.4)=1.58, p=0.22] or Condition x Scene [F(2,60.4)=1.10, p=0.34].

PRS Fascination did not significantly differ by Condition (0.48, 95% CI [−0.28, 1.24], p=0.21). However, there was a significant effect of Scene [F(2,60.0)=7.45, p=0.0013] and no Condition x Scene interaction [F(2,60.0)=0.16, p=0.86]. Averaged over Condition, Fascination was significantly higher in the Forest (0.54, 95% CI [0.08, 0.99], p=0.03) and Beach (0.88, 95% CI [0.42, 1.33], p < 0.001) than in the Garden. Simple effects contrasts showed that Fascination for the VR+OWT group was significantly higher in the Beach than the Garden (0.99, 95% CI [0.37, 1.62], p=0.01).

Finally, PRS Total Presence did not significantly differ by Condition (0.21, 95% CI [−0.29, 0.70], p=0.40). The main effect of Scene approached significance [F(2,60.0)=3.05, p=0.055], and there was not a significant interaction of Condition x Scene [F(2,60.0)=0.20, p=0.82].

Longitudinal Changes: Affect and Stress

Figure 4 show PANAS PA, PANAS NA, and Perceived Stress Scale (PSS) scores over time (days since T1) by Condition (Control, VR, VR + OWT), and Table 1 summarizes the results from the LMM analysis.

For PANAS PA, there was not a significant effect of Condition, Time, or their interaction (all p>0.25). For PANAS NA, there was a significant effect of Time [F(1,100.21)=5.09, p=0.03], and a significant Condition x Time interaction [F(2,100.13)=5.40, p=0.037]. Simple slopes analysis revealed that PANAS NA significantly decreased over Time for the VR group (−0.20, 95% CI [−0.38, −0.03], p=0.035) and the VR+OWT group (−0.20, 95% CI [−0.38, −0.03], p=0.035), but not for the Control group (0.07, 95% CI [−0.10, 0.24], p=0.41). The rate of change for the VR and VR+OWT groups was significantly different from the Control group (both p=0.04), but not significantly different from each other (p=0.99).

For the Perceived Stress Scale (PSS), there was a significant main effect of Time [F(1,48.5)=78.98, p < 0.001) but not Condition or Condition x Time (p > 0.28). Averaged across Condition, PSS decreased by −0.23 points per day (95% CI [−0.28, −0.18], p < 0.001). Simple slopes analysis showed that PSS significantly decreased with Time for all groups (Control: −0.18, 95% CI [−0.27, −0.10], p < 0.001; VR: −0.21, 95% CI [−0.30, −0.12], p < 0.001; VR+OWT: −0.28, 95% CI [−0.37, −0.19], p < 0.001). The rate of

change was highest for the VR+OWT group and lowest for the Control group, but there was no significant difference in slope between any of the three groups.

Longitudinal Changes: Cognitive Performance

Table 2 reports the results from the mixed models analysis for the 19 Cognition speed and accuracy metrics. Model predictions with 95% confidence intervals are provided in Supplementary Figure 1 and Supplementary Figure 2. A significant Condition x Time interaction was observed for reaction times on the Abstract Matching (AM), Line Orientation Test (LOT), and Balloon Analog Risk Test (BART) and for accuracy on the Emotion Recognition Task (ERT).

For AM reaction time (RT), there was a significant main effect of Time [Wald $\chi^2(2)=4.32$, $p=0.038$], and Condition x Time [Wald $\chi^2(2)=10.36$, $p=0.006$]. Simple slopes analysis showed that AM reaction times significantly increased (worsened) for the Control (15.36 ms/day, 95% CI [3.91, 26.8], $p=0.024$) and VR+OWT group (14.67 ms/day, 95% CI [2.71, 26.63], $p=0.024$) but not the VR group (−0.85 ms/day, 95% CI [−20.22, 3.20], $p=0.15$). Additionally, slopes for the Control and VR+OWT group were significantly greater than the VR group (both $p=0.01$).

For LOT RT, there was a significant interaction between Condition and Time [Wald $\chi^2(2)=10.13$, $p=0.006$]. Simple slopes analysis showed that LOT RT significantly increased for the Control group (49.10, 95% CI [10.63, 87.56], $p=0.037$), and reaction times tended to improve (decrease) for the VR group (−39.42, 95% CI [−78.76, −0.09], $p=0.07$) and VR+OWT group (−4.71 ms/day, 95% CI [−44.90, 35.48], $p=0.82$), though not significantly.

For BART RT, there was a significant main effect of Time [$F(1,99.7)=6.95$, $p=0.010$] and Condition x Time [$F(2, 99.7)=5.80$, $p=0.004$]. Simple slopes analysis showed that reaction time significantly increased (worsened) for the Control group only (24.28 ms/day, 95% CI [13.23, 35.33], $p < 0.001$). Furthermore, the rate of change for the Control group was significantly larger than the VR ($p=0.009$) and VR+OWT groups ($p=0.008$).

For ERT accuracy, there was a significant interaction between Condition and Time [$F(2,103.77)=3.59$, $p=0.031$]. Simple slopes analysis revealed that the rate of change for the VR group was significantly less than the Control and VR+OWT groups (both $p=0.034$), though the rate of change did not significantly differ from zero for any group (all $p>0.1$).

Averaged over Condition, reaction time decreased over time on the Motor Praxis (MP) test (−1.7 ms/day, 95% CI [−3.26, −0.14], $p=0.032$) and increased on the Digit Symbol Substitution Task (DSST) (3.69 ms/day, 95% CI [2.25, 5.14], $p < 0.001$). Over time, accuracy decreased on the AM (−0.002, 95% CI [−0.004, −0.0005], $p=0.011$) and increased on the Matrix Reasoning Test (MRT) (0.003, 95% CI [0.0003, 0.0051], $p=0.028$). BART Risk Score significantly decreased over time (−0.002, 95% CI [−0.004, −0.0004], $p=0.018$).

Averaged over time, there were significant group-wise differences on the MRT RT and DSST accuracy. The Control group had significantly higher (worse) average reaction times than both the VR ($p < 0.001$) and VR+OWT ($p=0.039$) groups, and the VR+OWT group had significantly lower (better) reaction times than the VR group ($p=0.039$). Averaged over time, accuracy on the DSST also tended to be higher for the Control and was significantly different from the VR group ($p=0.044$) but not the VR+OWT group ($p=0.07$).

Qualitative Feedback

Most participants in both VR and VR+OWT groups said they would use the intervention again (VR: 12/17; VR+OWT: 15/17). Many also described immediate benefits including relaxation, reduced stress, improved mood or focus, or a sense of calm (VR: 14/17; VR+OWT: 11/17). Participants frequently characterized the experience as a “break from the day” that allowed them to disengage from ongoing stressors. One participant described feeling “more calm,” likening the experience to a state of relaxation immediately after waking. Notably, two participants in the VR+OWT group reported sustained benefits lasting hours or even days after VR use.

The proportion of participants selecting each scene as their favorite or least favorite is shown in Figure 5 (excluding one VR participant who completed only one scene). The Forest was the most frequently chosen favorite (45.5%; VR: 6, VR+OWT: 9), followed by the Beach (36.4%; VR: 8, VR+OWT: 4), and Garden (18.2%; VR: 2, VR+OWT: 4). Conversely, the Garden was most often selected as the least favorite scene (51.5%; VR: 12, VR+OWT: 5), followed by the Forest (27.3%; VR: 2; VR+OWT: 7) and the Beach (21.2%; VR: 2; VR+OWT: 5).

Across scenes, favorite environments were most commonly described as offering exploration and interactivity, including climbing and object manipulation (e.g., stacking rocks). Scene realism, including visual and auditory fidelity, was also cited as a contributing factor. Least favorite scenes were typically described as restrictive, small in scale, or lacking opportunities for interaction.

Olfactory, Wind, and Thermal Stimuli: Participants in the VR+OWT group generally responded positively to olfactory, wind, and thermal stimuli, frequently noting that these cues enhanced immersion and environmental realism. Several participants described moments in which the multisensory feedback felt sufficiently realistic to evoke real-world expectations, such as warmth prompting thoughts of sun exposure. Others emphasized that dynamic changes in temperature, airflow, and scent helped align the experience with how outdoor environments are encountered in daily life, contributing to relaxation and embodied presence.

“It was what makes it real. If you only see the VR, like the screen, you would feel like you are watching a show in 3D. But with the wind, the smell, and the heat, to pull all your senses in, your whole body is in the VR environment, not only your eyes.”

When asked which additional stimulus they would retain if only one could remain, preferences were evenly distributed across scent (n = 7), temperature (n = 5), and wind (n = 5). Participants consistently described all three as difficult to replicate and as critical contributors to realism. Scents were valued for novelty and relaxation, temperature for enhancing immersion and realism, and wind for its dynamic, multidirectional qualities that made participants feel physically surrounded by the environment. Synchronizing auditory wind cues with fan intensity also contributed to "a sense of movement in the area."

Despite these benefits, multisensory augmentation also introduced challenges. Several participants reported that certain scents—particularly floral odors in the Garden—were too strong or distracting. Thermal feedback was occasionally described as uncomfortable or unrealistic, especially when heat intensity was high or temperature transitions were abrupt. One participant reported avoiding areas that they associated with excessive heat, and the maximum heating intensity was reduced for three participants due to discomfort with the thermal devices. Sensory mismatches, such as entering water without a corresponding temperature change, as well as fan noise, also occasionally disrupted immersion.

Participants also provided feedback on the overall system. Several requested clearer guidance regarding which objects were interactive and where to find them, as well as clearer navigation boundaries to indicate map limits. Inconsistent abilities between scenes, such as being able to climb rocks in the Beach but not in the Garden or Forest, were another source of frustration. Participants also expressed interest in additional interactive elements, wildlife, smoother visual rendering, lighter or wireless headsets, faster movement speeds, and optional light gamification (e.g., collecting objects or completing low-stakes challenges).

Discussion

This experiment evaluated the restorative, psychological, and cognitive effects of a nature VR intervention with varying levels of sensory stimulation (audiovisual stimuli versus audiovisual, olfactory, wind, and thermal stimuli). A unique factor in ICE environments is reduced sensory stimulation and monotony, which contributes to boredom, frustration, and stress [29]. Multisensory VR nature experiences could provide benefits on two fronts: 1) providing enriching sensory input; and 2) providing immersive access to natural environments. While prior work has demonstrated psychophysiological and cognitive benefits of virtual nature, most studies have relied on limited sensory stimulation and focused on immediate outcomes. Here, we found that virtual nature exposure produced both immediate and sustained reductions (improvement) in negative affect for both audiovisual VR and multisensory VR (VR+OWT). The addition of olfactory, wind, and thermal stimuli enhanced presence in certain scenes, whereas perceived restorativeness was influenced more strongly by scene content than by sensory immersion.

These findings extend previous work on affective responses to virtual nature. Consistent with earlier studies, exposure to virtual natural environments significantly reduced negative affect while maintaining positive affect [13,16,30–32]. In line with Attention Restoration Theory [9], reductions in negative affect may facilitate psychological disengagement from everyday demands, allowing mental resources to be redirected away from negative mental mechanisms [33] and maladaptive thought patterns [34]. Prior work suggests that positive affective responses to nature depend on the availability of evolutionarily relevant resources or hazards and may differ between real and simulated environments [35]. Because simulated nature does not afford physical access to such resources, positive affect may be maintained rather than enhanced, providing a potential explanation for the present findings.

Although affective responses were comparable across groups, multisensory augmentation significantly enhanced presence, particularly in General Presence, Involvement, and Total IPQ scores. Notably, these effects were scene dependent. Participants in the audiovisual VR condition reported reduced Involvement and Total Presence in the Garden and Forest relative to the Beach, whereas presence scores in the VR+OWT condition were more consistent across scenes. This suggests that multisensory augmentation helped elevate less-preferred environments, enhancing sense of presence and enjoyment. Scene preference data mirrored this trend: the Garden was clearly least preferred in the VR group, while preferences were more evenly distributed in the VR+OWT group.

Perceived restorativeness was largely determined by scene content, with similar PRS scores observed across sensory conditions. The Garden was characterized with lower Fascination and higher Coherence relative to the Forest and Beach. Coherence reflects the perceived connectedness and scope of an environment [9,36]. Given the Garden had the smallest map size, its higher Coherence likely reflected connectedness rather than expansiveness. The inclusion of structured elements such as paths, bridges, and benches may have reinforced this sense of organization. In contrast, the relatively ordinary nature of the Garden, compared to the more expansive and novel Forest and Beach environments, may have contributed to its lower Fascination scores. Together, these findings indicate that multisensory cues primarily influenced presence, whereas restorativeness was driven more strongly by scene characteristics.

Interestingly, PRS Coherence in all scenes tended to be lower in VR+OWT condition–a rare, though non-significant reversal of group trends. These patterns likely reflect sensory mismatches and echo broader discussions of "credibility" [37] and "believability" [38] in VR environments, emphasizing that sensory realism alone is not sufficient. Rather, the alignment of multisensory cues with environmental context is critical to support coherence, as mismatches between expected and delivered sensory input can detract from the virtual experience [39–41]. These findings highlight that multisensory augmentation can both enhance and undermine the VR experience, depending on implementation.

Scene-level differences revealed that the Beach tended to evoke stronger Involvement and Total Presence for the audiovisual VR group and higher Fascination in both conditions. Features such as the moving waves, underwater exploration, and climbable rock formations may have added visual interest

and increased engagement compared to the Garden and Forest. The prominent aquatic component may also have played a role, consistent with evidence that “blue spaces” are associated with enhanced affective and restorative outcomes [42].

Overall, multisensory augmentation enhanced presence and helped equalize enjoyment across environments, while affective benefits and perceived restorativeness remained largely comparable between groups. In some cases, however, thermal and wind cues acted as distractions, reducing coherence. Participants were especially sensitive to temperature mismatches, underscoring the need for more precise environmental mapping of thermal stimuli. Participant preferences also favored cooling sensations, suggesting that future designs may benefit from emphasizing cooler temperatures, reducing maximum heat intensity, and calibrating thermal feedback on an individual basis.

Several technical improvements could further enhance the multisensory experience. For example, ray-casting techniques could detect visual occlusions (e.g., shade from trees) and dynamically adjust thermal feedback. Cooling sensations when entering water and more gradual temperature transitions would better align sensory cues with environmental context. Reducing fan noise and incorporating noise-canceling headphones may further improve immersion.

Unlike affect and stress, cognitive performance remained largely stable over time. While some time-dependent trends and group-by-time interactions emerged, results were mixed and did not reveal consistent cognitive benefits associated with either VR condition. These findings suggest that observed cognitive changes may reflect external influences rather than systematic effects of the intervention. This interpretation is consistent with prior work indicating that cognitive and psychological benefits of nature exposure may operate through distinct mechanisms [43–45]. Given evidence that nature can provide immediate cognitive benefits [44–47], future research should more closely examine the temporal dynamics of these effects.

Several limitations warrant consideration. First, some longitudinal assessments (T2 and T3) occurred shortly after VR exposure, raising the possibility of carry-over effects that may have contributed to reductions in negative affect. Second, the experimental environment and participant population differed substantially from ICE environments. Although academic stressors are significant [48,49], they do not produce the same psychological or cognitive vulnerabilities as ICE environments. Nonetheless, the findings provide valuable insight into the potential of multisensory VR as a well-being countermeasure.

Third, although cybersickness was minimized through the use of teleportation-based locomotion, mild symptoms were reported in a small number of sessions. Technical issues, particularly instability in Bluetooth connections to thermal devices, may also have affected the consistency of sensory feedback. Fourth, cognitive performance was assessed weekly, which may have limited sensitivity to short-term cognitive changes. Finally, while the study compared audiovisual VR to multisensory VR, it did not isolate the contributions of individual sensory modalities. Participant feedback nevertheless suggests that the combined and synchronized presentation of cues was central to the immersive experience.

Future work should prioritize personalization, as participants varied widely in their sensory preferences and responses. Customizing temperature ranges, olfactory intensity, environmental features, or scene selection may enhance benefits. For example, a crew to Mars could have a personalized experience that is refined during the period leading up to the mission. When personalized environment are impractical, offering a broader range of options could be a feasible alternative. Integrating mindfulness practices may further amplify restorative effects, as several participants spontaneously engaged in meditative behaviors during VR exposure and prior work supports synergistic benefits [50–53]. While scenes here were intentionally not gamified to isolate the effects of nature exposure, gamified elements could also reap positive benefits [54], and participants were often observed creating their own informal challenges during exploration.

In summary, both audiovisual and multisensory VR reliably reduced negative affect immediately and over time. Multisensory augmentation enhanced presence and balanced scene enjoyment but was sensitive to mismatches in sensory feedback, particularly thermal cues. Cognitive performance remained stable, suggesting that long-term affective benefits may not directly translate to sustained cognitive improvements within the study timeframe. Together, these findings highlight both the promise and complexity of multisensory VR countermeasures, emphasizing the importance of sensory coherence, personalization, and interactivity in future designs. Beyond spaceflight and ICE environments, such interventions may also benefit other nature-deprived populations, including nursing home residents, post-operative patients, and large city residents in our increasingly urbanized world.

Methods

Participants

We recruited healthy young adults from Texas A&M University and the surrounding area. Fifty-one participants (30 male; mean age = 24.1 ± 2.9 years) completed the study. All participants reported color vision, no anosmia (i.e., lost part or all of their sense of smell), and no history of neurological disorders. Individuals with high susceptibility to motion or simulator sickness were excluded to reduce the likelihood that they could not complete the study. The protocol was approved by the Institutional Review Board at Texas A\&M University (IRB2023-0944D) in accordance with the declaration of Helsinki. Informed consent was obtained from study participants prior to any data collection.

Experimental Design

A between-subjects design was employed (Figure 6). Participants were randomly assigned to one of three groups: 1) control (no VR); 2) VR with audio and visual stimuli only (VR); or 3) VR with audio, visual, olfactory, wind, and thermal stimuli (VR+OWT). All participants first completed a Familiarization session, during which demographics and general health questionnaires were administered. Participants were then introduced to the Cognition test battery, a series of cognitive tasks that they would complete

periodically throughout the experiment. A standardized instructional presentation and video were provided, followed by shortened practice versions of 8 of the 10 Cognition tests (practice versions were not provided for the Visual Object Learning Task and the Balloon Analog Risk Task). Practice versions were available for subsequent administrations but were not required after the Familiarization session. Cognition data from the Familiarization session were not included in analyses.

The study duration was approximately two weeks (mean ± SD = 15.5 ± 2.4 days). T1 data collection (i.e., baseline) occurred at least one day after Familiarization. At T1, participants completed questionnaires assessing affect, stress, and a measure of cognitive performance. Participants in the VR and VR+OWT groups were additionally trained on use of the head-mounted display (HMD) and controllers and given a brief equipment practice period.

Follow-up assessments occurred approximately one week (T2) and two weeks (T3) after T1. At T2, participants completed measures of affect and cognitive performance. At T3, participants completed measures of affect, stress, cognitive performance, and participated in a semi-structured interview.

Between T1 and T3, participants in the VR and VR+OWT groups were eligible to complete up to five VR sessions on weekdays, with no more than one VR session per day. During each VR session, participants selected one of three VR environments (Garden, Forest, or Beach) and spent 15 minutes exploring freely. Navigation was primarily controller-based, with limited physical movement permitted within a 9 ft × 6 ft play area. After each session, participants completed surveys assessing affect, perceived restorativeness, presence, and motion sickness symptoms.

All participants received $50 in gift cards for completing the study; participants in VR conditions received an additional $10 for each VR session they attended.

Virtual Reality Environments

Three computer-generated nature VR environments—a Garden, Forest, and Beach—were developed using Unreal Engine 5 (Figure 7). Participants experienced the VR environments using an HTC Vive Pro Eye headset (HTC Corporation, Xindian, New Taipei City, Taiwan).

The landscapes were selected to represent a range of environmental qualities previously associated with psychological restoration. The Garden combined built and natural elements and featured the highest plant biodiversity, which has been linked to enhanced restorative outcomes [55]. The Forest environment included mountainous terrain and a mix of deciduous and coniferous trees; forests are commonly used in restorative environment research and have been shown to confer substantial benefits, as reflected in practices such as forest bathing (Shinrin-yoku) [56]. The Beach environment, which included large rock formations and tropical vegetation, was selected because aquatic settings have been associated with increased restorative effects [42]. Accordingly, all scenes incorporated an aquatic element. Across environments, tree branches swayed in the wind, and no people or animals were included. Additional

details for each scene are provided in Table 3 and videos of these environments are available at: https://youtu.be/7tHSgggd-Hk?si=_FyNg8sAoR39K2aO..

Each environment included spatialized 3D audio that adapted to the user's surroundings to enhance realism and reduce repetition [57]. Audio consisted of a continuous ambient base layer, location-specific sounds (e.g., waves near the shoreline), and randomized transient sound events (e.g., bird calls). These sounds were spatialized using interaural time and level differences, with distance-based attenuation to convey direction and proximity.

Based on feedback from prior work, each environment included two types of interactive, physics-based objects. Additionally, two locomotion methods were available, continuous movement and point-and-teleport, and participants could toggle between them during the experience. Teleportation was included to reduce motion sickness while preserving user control [58].

Dynamic olfactory, wind, and thermal stimuli were implemented in the VR+OWT condition. These stimuli were spatially mapped within each environment and varied based on the user's location (Figure 8).

Olfactory stimuli: Scents were delivered using a Compact Scent Generator (Olorama Technology Ltd, Valencia, Spain) following methods from a previous study [30]. Specific aromas were triggered based on proximity to environmental features (e.g., wet ground near water). The Garden environment included the aromas of fresh grass, rosemary, roses, blossom, and wet ground; the Forest featured fresh grass, lavender, pine, wet ground, and woods; and the Beach included beach scent, fresh grass, and wet ground.

Wind stimuli: Wind was delivered via three external fans placed in a triangular arrangement around the play area. Each fan was controlled by an electronic speed controller connected to an Arduino Nano microcontroller. Unreal Engine sent real-time fan commands via serial communication, sending a single digit integer (0–9) to each fan that was mapped to pulse widths (1100–1475 μs) controlling fan speed. Wind audio volume was synchronized with fan intensity.

Thermal stimuli: Thermal sensations were delivered using ThermoReal flexible thermoelectric devices (TEGway, Daejeon, South Korea), worn on the arms and attached to the HMD. Devices communicated wirelessly via Bluetooth and operated using a pulsed pattern (6 seconds on, 2 seconds off). Intensity values ranged from 1.0 to 10.0, with 1.0–5.9 producing cold and 6.0–10.0 producing heat. Pilot testing established comfort thresholds, and intensities were capped at 3.5 (cold) and 7.25 (heat) on the arms, and 6.25 (heat) on the forehead.

Thermal and wind stimuli were spatially mapped to predefined environmental zones. Shaded areas were assigned to cooler temperatures and lower wind speeds, whereas open areas were assigned to warmer temperatures and higher wind speeds. To enhance naturalism, both thermal and wind stimuli included small random fluctuations in intensity.

Dependent Variables

Self-report surveys were administered to assess participants' psychological mood and their experience in VR throughout the experiment. Additionally, a cognitive test battery was used to evaluate cognitive performance over time.

Experiences in Virtual Reality

iGroup Presence Questionnaire (IPQ): Presence was assessed using the IPQ [28,59,60]. Participants responded to 14 statements on a 7-point Likert scale. Items belonged to one of three subscales (Spatial Presence, Involvement, and Experienced Realism) and a fourth factor, General Presence, which consisted of a single item. Internal reliability (McDonald's omega) was ω = 0.71, ω = 0.75, and ω = 0.70 for Spatial Presence, Involvement, and Experienced Realism, respectively.

Perceived Restorativeness Scale (PRS): The 16-item PRS [36] assessed the restorative quality of the VR environment across four subdomains aligned with Attention Restoration Theory: Being Away, Fascination, Coherence (extent), and Compatibility. Participants rated the extent to which each statement described their most recent VR experience on a 7-point Likert scale (0 = not at all, 6 = completely). Items within each subscale were averaged, and Coherence items were reverse-scored so that higher values indicated greater perceived Coherence. Internal reliability (McDonald's omega) was ω = 0.89 for Being Away, ω =0.94 for Fascination, ω =0.78 for Coherence, and ω =0.93 for Compatibility.

Psychological State

Positive and Negative Affect Schedule (PANAS): Affect was measured using the PANAS [61], consisting of 10 positive (e.g., interested, excited, strong) and 10 negative (e.g., distressed, upset, nervous) affect items. Participants rated the extent to which they experienced each emotion using a 5-point Likert scale (1 = very slightly or not at all, 2 = a little, 3 = moderately, 4 = quite a bit, 5 = extremely). Subscale scores were summed, with higher values indicating greater affect. Internal reliability (McDonald's omega) was ω = 0.88 for positive affect (PA) and ω = 0.89 for negative affect (NA).

Perceived Stress Scale (PSS): Perceived stress was measured using a 4-item version of the PSS [62]. Items were rated on a 5-point scale (0 = never, 1 = almost never, 2 = sometimes, 3 = fairly often, 4 = very often), with two items reverse-scored. Responses were summed to generate a total stress score, with higher scores indicating greater perceived stress. Internal reliability (Cronbach's alpha) for the total PSS was α = 0.77.

Qualitative Feedback

After each VR session, participants reported any VR sickness symptoms and provided optional open-ended feedback. At T3, participants completed a semi-structured interview addressing favorite and least

favorite scenes, perceived benefits, willingness to reuse the intervention, and (for VR+OWT participants) perceptions and preferences regarding multisensory stimuli.

Cognitive Performance

Cognitive performance was assessed using the *Cognition* battery (v3.0.9), comprised of 10 distinct neurobehavioral tasks designed to evaluate a broad spectrum of cognitive domains, including attention, memory, executive function, and processing speed [63]. The 10 tasks (Motor Praxis (MP) task, Visual Object Learning Test (VOLT), Fractal 2-Back (F2B), Abstract Matching (AM) test, Line Orientation Test (LOT), Emotion Recognition Task (ERT), Matrix Reasoning Test (MRT), Digit Symbol Substitution Task (DSST), Balloon Analog Risk Test (BART), and Psychomotor Vigilance Test (PVT)) are described in Supplementary Table 1. Testing was conducted on a laptop using Joggle Research software (Pulsar Informatics Inc., Philadelphia, USA).

Performance on all tasks was measured through two metrics: an accuracy metric and a speed metric. Accuracy outcomes spanned a range of 0 to 1, with 1 signifying optimal performance. Conversely, lower values in speed outcomes denote shorter response times, indicating higher speed.

For most tasks, accuracy was calculated as the proportion of correct responses, and the speed metric is reported as the mean reaction time over the task duration. Accuracy was not calculated for the Motor Praxis (MP) task because the instructions for this task did not emphasize accuracy. For the Fractal 2-Back (F2B) test, accuracy was calculated as the average proportion of correctly identified targets and the proportion of correctly identified decoys (correct non-responses). In the Line Orientation Test (LOT), accuracy was calculated as 3 minus the average number of clicks off, divided by 3. If the average number of clicks off was greater than 3, then the accuracy score was set to 0. In the Balloon Analog Risk Test (BART), the number of pumps was divided by the total number of possible pumps across all 30 balloons to calculate a Risk Score. The speed metric for the PVT was calculated as 10 minus the average reciprocal reaction time (1/[Reaction time in seconds]) across the task, as this has been shown to have greater sensitivity compared to standard reaction time [64]. Accuracy in the PVT was calculated as shown in Equation 1:

$$PVT\ accuracy = 1 - \frac{N\ lapses + N\ false\ starts}{N\ stimuli + N\ false\ starts} \qquad (1)$$

where responses ≤ 100 ms were labelled as false starts and responses ≥ 355 ms were labelled as lapses. Speed and accuracy metrics were adjusted for both stimulus set effects and practice effects using a “short” administration interval using methods described in previous research [65].

Statistical Analysis

Data were screened for quality prior to analysis. One Cognition DSST run was excluded due to noncompliance. Linear mixed models (LMMs) were used to assess immediate and longitudinal effects, with subject included as a random intercept. When assumptions were violated, robust linear mixed models (RLMMs) were used because they are less sensitive to deviations from normality and missing data [66]. Model fit was evaluated through tests for dispersion, outliers, and distribution (i.e., Kolmogorov-Smirnof) using the DHARMa package. Residual heteroscedasticity was assessed using Levene's test.

Overall significance of the main effects and interactions was evaluated using an omnibus F-test on the estimated marginal means (joint tests from the emmeans package) with the Kenward-Rogers approximation for degrees of freedom. RLMMs were evaluated using an asymptotic Wald χ^2 test as the Kenward-Rogers approximation is not supported for robust models. Follow up post-hocs were conducted as described in the paragraphs below.

Immediate Effects of VR Intervention

Because participants could repeat VR scenes, post-VR PANAS, IPQ, and PRS scores were first averaged per scene (Garden, Forest, Beach) for each participant for LMM analysis. Fixed factors for PANAS models included Condition [categorical: VR or VR+OWT], Scene [categorical: T1, Garden, Forest, Beach], and the interaction Condition x Scene. Fixed factors for the IPQ and PRS models were Condition [categorical: VR or VR+OWT], Scene [categorical: Garden, Forest, Beach], and the interaction Condition x Scene. PANAS NA residuals violated the normality assumption and IPQ General Presence residuals were heteroscedastic, so these outcomes were refit using RLMM.

Significant effects of Condition, Scene, or their interaction were followed by post-hoc contrasts. When an interaction effect was present, simple effects contrasts were conducted in two ways: first, each Scene (Garden, Forest, Beach) was compared within each Condition (VR group vs VR+OWT group); and second, Condition was compared within each Scene. When the interaction was not significant, main effect contrasts were evaluated in two ways: first, comparing each scores for each Scene (Garden, Forest, Beach) averaged over Condition (VR group and VR+OWT group); and second, comparing each Condition averaged over all Scenes. When a main effect contrast was significant, follow up simple effects contrasts were performed according to the procedures described above.

For PANAS scores, two additional contrasts were specified: the first contrast compared the VR group versus the VR+OWT group at T1 (i.e., baseline); and the second contrast compared the VR group versus the VR+OWT group averaged across all post-VR points (i.e., Garden, Forest, Beach).

Longitudinal Changes

PANAS, PSS, and all Cognition speed and accuracy metrics were analyzed using LMMs and RLMMs. Fixed effects included Condition (Control, VR, or VR+OWT), Time (days since T1), and their interaction (Condition x Time). When Condition effects were significant, post-hoc contrasts were performed on the estimated marginal means averaged across Time. To assess changes over time, marginal trends (slopes) were estimated for each Condition. When the effect of Time was significant, follow-up simple slopes analyses were conducted to test whether each group-specific slope differed from zero. Significant slopes were then compared pairwise to determine whether rates of change differed between groups.

The Benjamini and Hochberg correction was applied to adjust p-values and control for false discovery rate in both immediate and longitudinal analyses, with significance set at $\alpha = 0.05$. All statistical analyses were conducted in R version 4.4.2. LMMs and RLMMs were fit using the lme4 [67] and robustlmm [66] packages. Model diagnostics were assessed using the lmerTest [68] and DHARMa packages [69]. Adjusted means, slopes, and contrasts were calculated using the emmeans package [70].

Declarations

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Author Contributions

Conceptualization: R.A., A.D.A.; Data acquisition: R.A.; Analysis and interpretation: all authors; Funding acquisition: R.A., A.D.A.; Methodology: R.A., S.B., A.D.A.; Project administration: R.A., A.D.A.; Writing – original draft: R.A.; Writing – review and editing: all authors.

Data Availability

The datasets analyzed during the current study are available in the BHP-Lab repository, https://github.com/BHP-Lab/Immersive-VR/tree/main/SciRep%20Paper.

Additional Information

The authors declare no competing interests.

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Tables

Table 1: Summary of statistical results for PANAS Positive Affect, PANAS Negative Affect, and Perceived Stress Scale (PSS) linear mixed models. Fixed factors included Time [numeric: days since T1], Condition [categorical: Control, VR, or OVR], and the interaction Time x Condition. Subjects were included as random factors. Overall significance of the main and interaction effects were assessed using an omnibus F-test on each model with the Kenward-Rogers approximation for degrees of freedom. Bold values indicate significance ($p < 0.05$).

	P value		
Variable	Condition	Time	Condition x Time
PANAS PA	0.25	0.54	0.31
PANAS NA	0.85	**0.026**	**0.037**
PSS	0.97	**<0.001**	0.28

Table 2: Summary of statistical results for Cognition linear and robust linear mixed models. Fixed factors included Time [numeric: days since T1], Condition [categorical: Control, VR, or VR+OWT], and the interaction Condition x Time. Subjects were included as random factors. Overall significance of the main and interaction effects were assessed using an omnibus F-test with the Kenward-Rogers approximation for degrees of freedom for each model or an asymptotic Wald χ^2 test for robust models. †denotes robust models. VOLT: Visual Object Learning Test; F2B: Fractal 2-Back; AM: Abstract Matching; LOT: Line Orientation Test; ERT: Emotion Recognition Task; MRT: Matrix Reasoning Test; DSST: Digit Symbol

Substitution Task; BART: Balloon Analog Risk Test; PVT: Psychomotor Vigilance Test; MP: Motor Praxis. Bold values indicate significance ($p < 0.05$).

		P value		
Variable	**Units**	Condition	Time	Condition x Time
Speed Metrics				
VOLT RT	ms	0.31	0.66	0.66
F2B RT	ms	0.90	0.45	0.73
AM RT†	ms	0.41	**0.038**	**0.006**
LOT RT†	ms	0.38	0.89	**0.006**
ERT RT	ms	0.18	0.62	0.90
MRT RT	ms	**<0.001**	0.12	0.18
DSST RT†	ms	0.94	**<0.001**	0.73
BART RT	ms	0.16	**0.010**	**0.004**
PVT Slowness†	$10 - 1/s$	0.45	0.35	0.18
MP RT†	ms	0.38	**0.032**	0.66
Accuracy Metrics				
VOLT Accuracy†	% [0-1]	0.73	0.84	0.26
F2B Accuracy†	% [0-1]	0.71	0.77	0.98
AM Accuracy†	% [0-1]	0.82	**0.011**	0.71
LOT Accuracy	% [0-1]	0.54	0.12	0.86
ERT Accuracy	% [0-1]	0.88	0.22	**0.031**
MRT Accuracy†	% [0-1]	0.68	**0.028**	0.16
DSST Accuracy†	% [0-1]	**0.035**	0.07	0.93
BART Risk Score	—	0.81	**0.018**	0.23
PVT Accuracy†	% [0-1]	0.87	0.84	0.88

Table 3: Descriptions and attributes of the three computer-generated VR scenes.

VR scene	Garden	Forest	Beach
Description	A small bamboo garden on a sunny day featuring a variety of vegetation (e.g., juniper, Japanese maple, and elm trees, rosemary, ginger lily, roses, hydrangeas) with a pond and island in the center.	A forest, in a valley between snowcapped mountains, composed of coniferous and deciduous trees with some sunny open lavender meadows.	A tropical beach near sunset with gentle ocean waves, large rock formations, and a palm tree jungle providing shady areas along the shore.
Sounds	Birds (e.g., cardinal, robin), frogs, wind, rustling leaves	Birds (e.g., finch, owl, woodpecker), insects (e.g., katydid, cricket), pond trickling, wind, rustling leaves	Birds (e.g., sandpiper, seagulls), insects (e.g., cicadas, crickets) ocean waves, wind, rustling grass
Scents	Fresh grass, rosemary, roses, blossom, and wet ground	Fresh grass, lavender, pine, and wet ground	Beach, fresh grass, and wet ground
Interactive items	Stones and sunflowers	Pinecones and mushrooms	Coconuts and starfish
Aquatic elements	Pond	Large pond	Ocean
Human-made elements	Benches, fences, bridge, path, and gazebo	Path and fences	Beach chair and umbrella
Approximate size	0.04 km^2	1.9 km^2	0.54 km^2

Figures

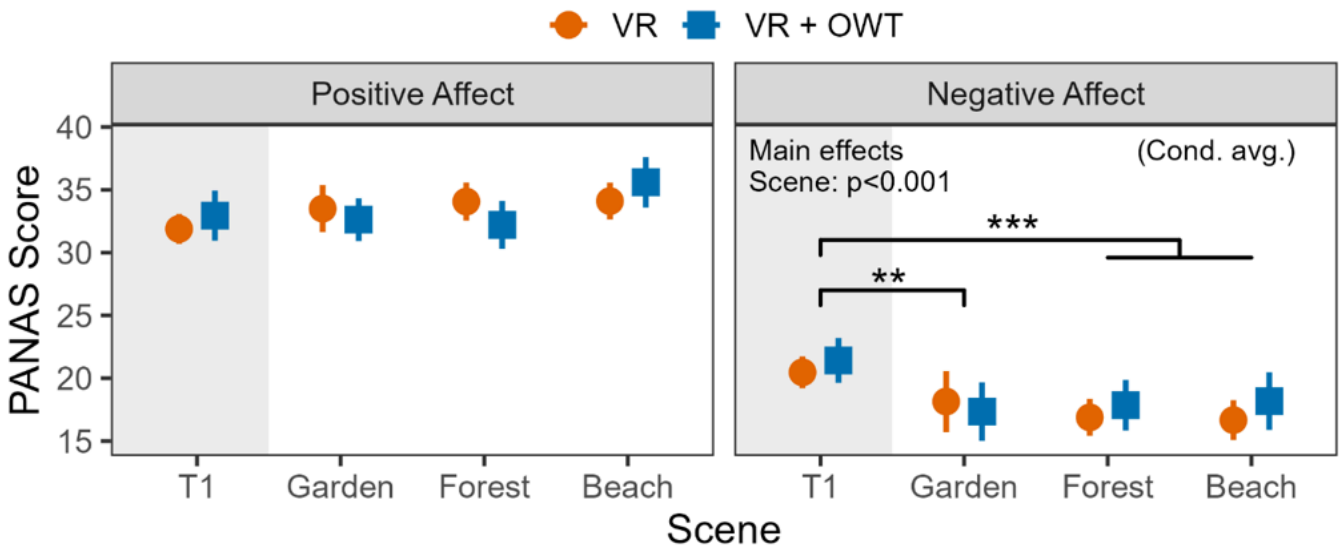


Figure 1

Positive and Negative Affect Schedule (PANAS) scores by Scene and Condition (VR: audiovisual VR group; VR+OWT: audiovisual, olfactory, wind, and thermal VR group). The T1 points correspond to baseline. The Garden, Forest, and Beach values were measured immediately after post-VR. If a subject did multiple VR sessions in the same scene, scores were averaged for those sessions. Scores may range from [10, 50]. Mean ± SE shown. Asterisk (*) denote significant differences between T1 and Post-VR (Garden, Forest, or Beach) for the estimated marginal means averaged over the factor Condition. **p < 0.01, ***p < 0.001.

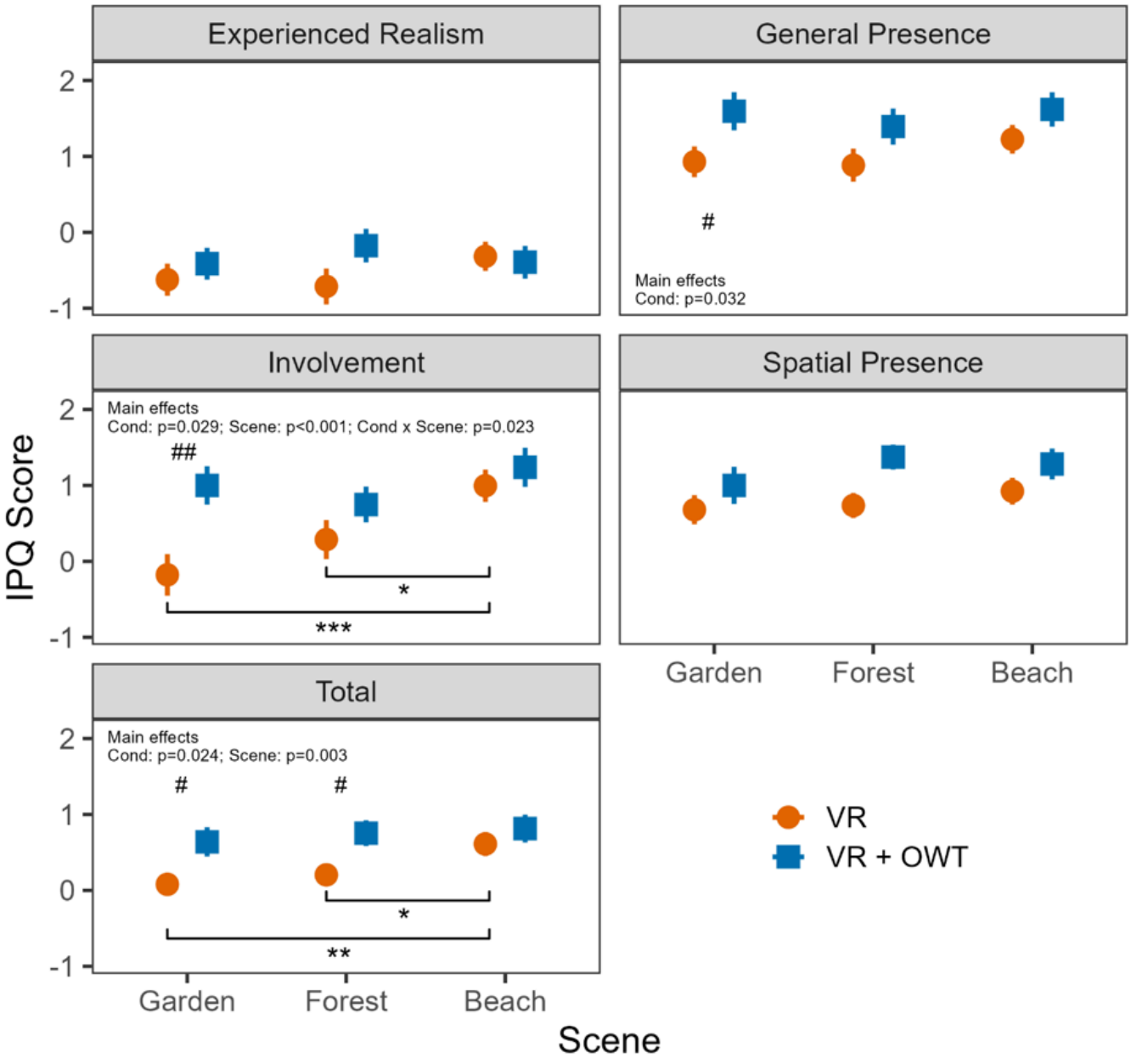


Figure 2

iGroup Presence Questionnaire (IPQ) scores by Scene and Condition (VR: audiovisual VR group; VR+OWT: audiovisual, olfactory, wind, and thermal VR group). IPQ scores are shown for the four subscales (Experienced Realism, General Presence, Involvement, and Spatial Presence) along with a Total Presence score. If a subject did multiple VR sessions in the same scene, scores were averaged for

those sessions. Data are presented as mean ± SE. Asteriks (*) indicate significant differences between scenes. Pound signs (#) indicate significant differences between the VR group and VR+OWT group. *p<0.05, **p<0.01, ***p<0.001.

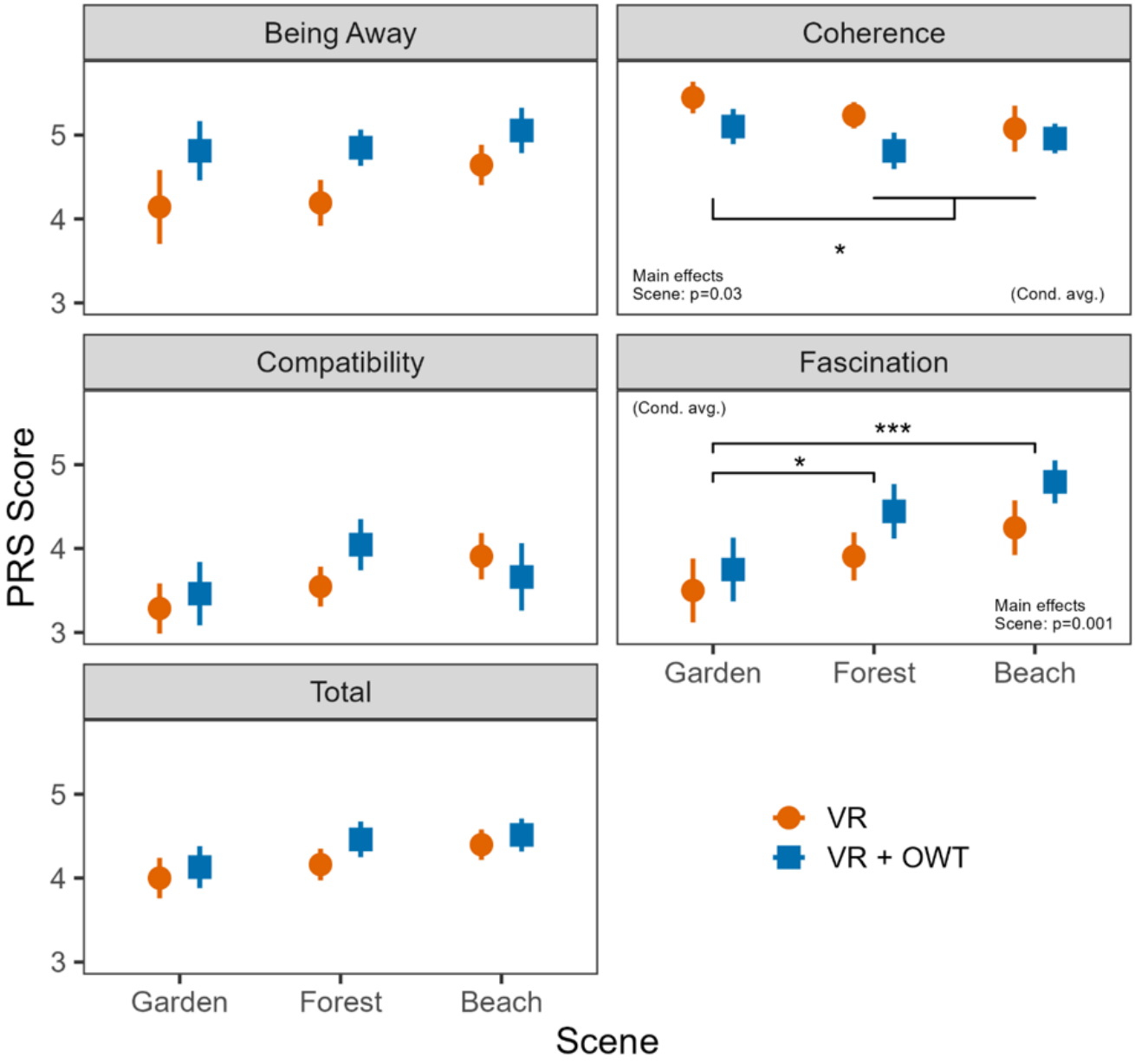


Figure 3

Perceived Restorativeness Scale (PRS) scores by Scene and Condition (VR: audiovisual VR group; VR+OWT: audiovisual, olfactory, wind, and thermal VR group). PRS scores are shown for the four subscales (Being Away, Coherence, Compatibility, and Fascination) along with a Total score. If a subject did multiple VR sessions in the same scene, scores were averaged for those sessions. Data are presented as mean ± SE. Asterisk (*) denote significant differences between VR Scenes (Garden, Forest, or Beach) for the estimated marginal means averaged over the factor Condition. *p<0.05, ***p<0.001.

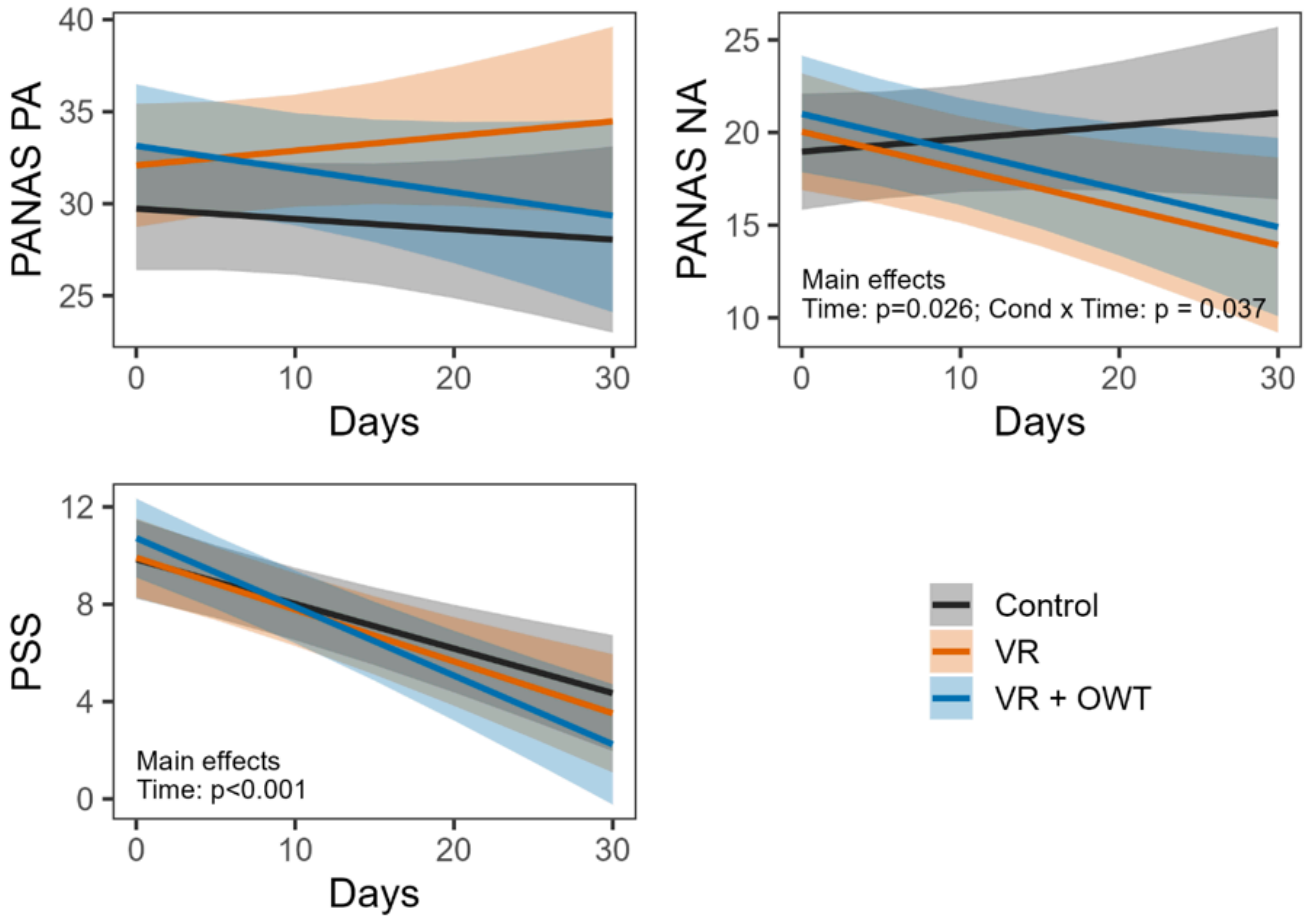


Figure 4

Linear mixed models for positive affect (PA), negative affect (NA), and perceived stress scale (PSS). Models are presented as predicted mean ± 95% confidence interval. Fixed factors included Time [days], Condition [categorical: Control, VR, VR+OWT], and the interaction Time x Condition. Subjects were included as random factors. PA: Positive Affect, NA: Negative Affect, PSS: Perceived Stress Scale.

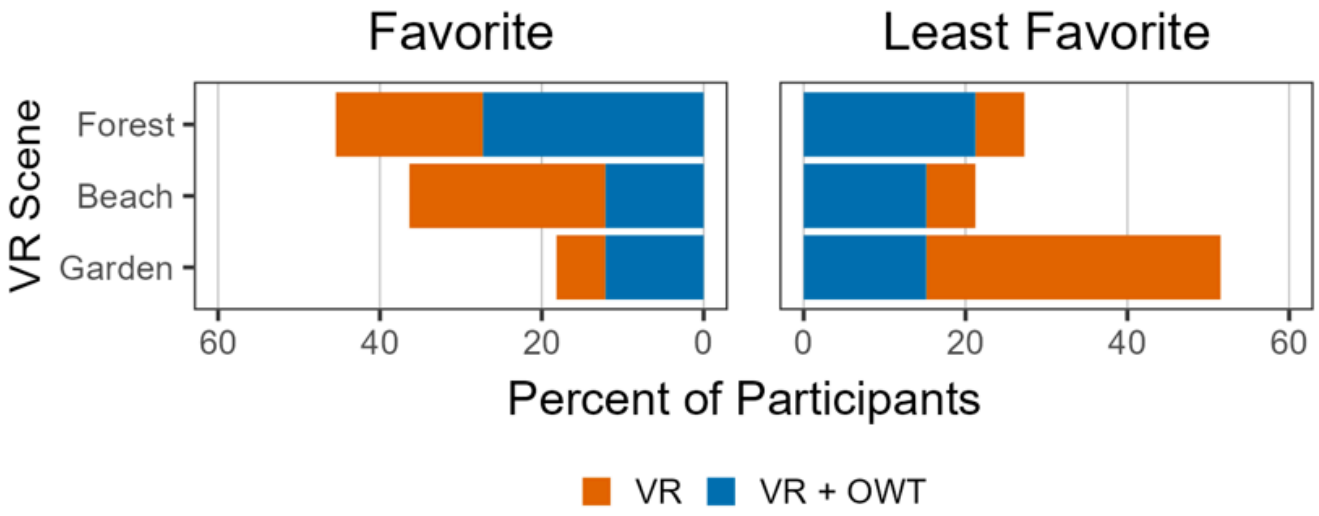


Figure 5

Favorite and least favorite VR scenes for the VR group (n = 16) and VR+OWT group (n = 17). One VR group participant that completed only one VR session was excluded.

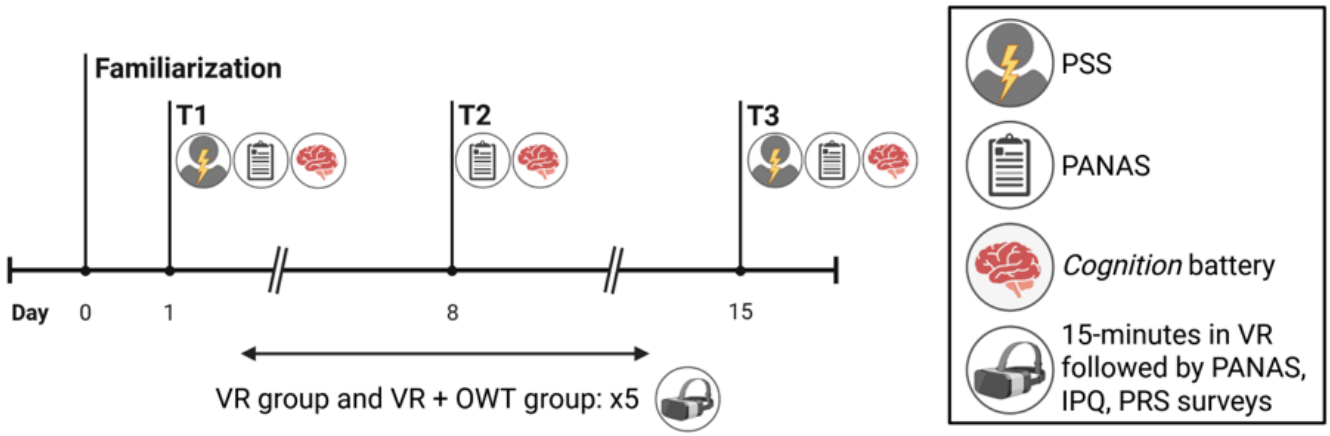


Figure 6

Overview of the experiment protocol. All groups completed surveys and the Cognition at the beginning of the study, approximately halfway through, and at the end of the experiment. Participants in the VR and VR+OWT groups were asked to complete up to 5 VR sessions during the intervention period. PSS: Perceived Stress Scale, PANAS: Positive and Negative Affect Scale, IPQ: iGroup Presence Questionnaire, PRS: Perceived Restorativeness Scale, VR: Virtual Reality, VR+OWT: Virtual Reality + olfactory, wind, and thermal stimuli.

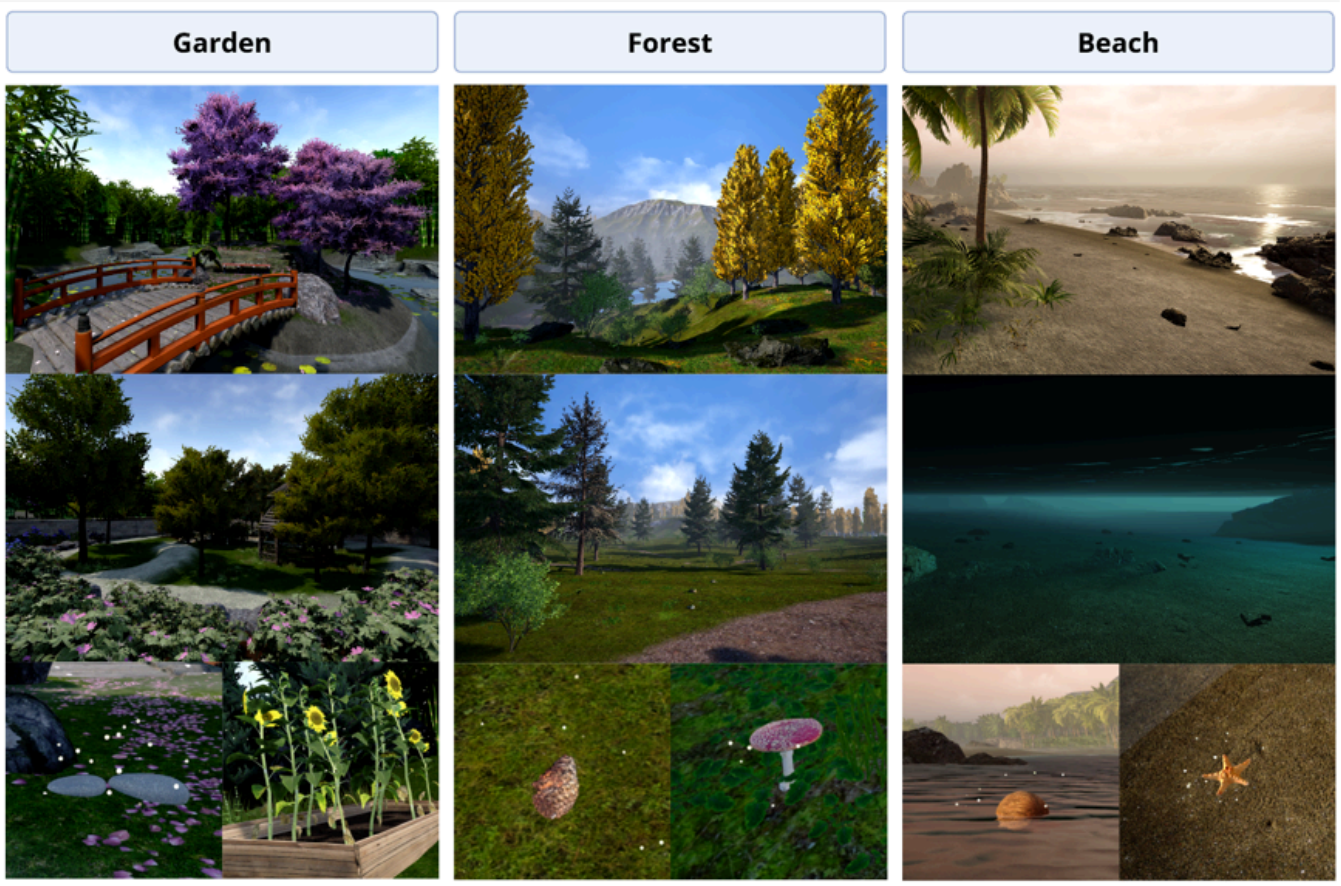


Figure 7

Representative screenshots from the three nature-inspired virtual reality environments used. Users could look underwater in the Beach scene. Images in the bottom row illustrate the two types of interactive, physics-based objects available in each scene: stones and sunflowers in the Garden, pinecones and mushrooms in the Forest, and coconuts and starfish in the Beach. Interactive objects were highlighted with particle “sparkle” effects to signal interactivity.

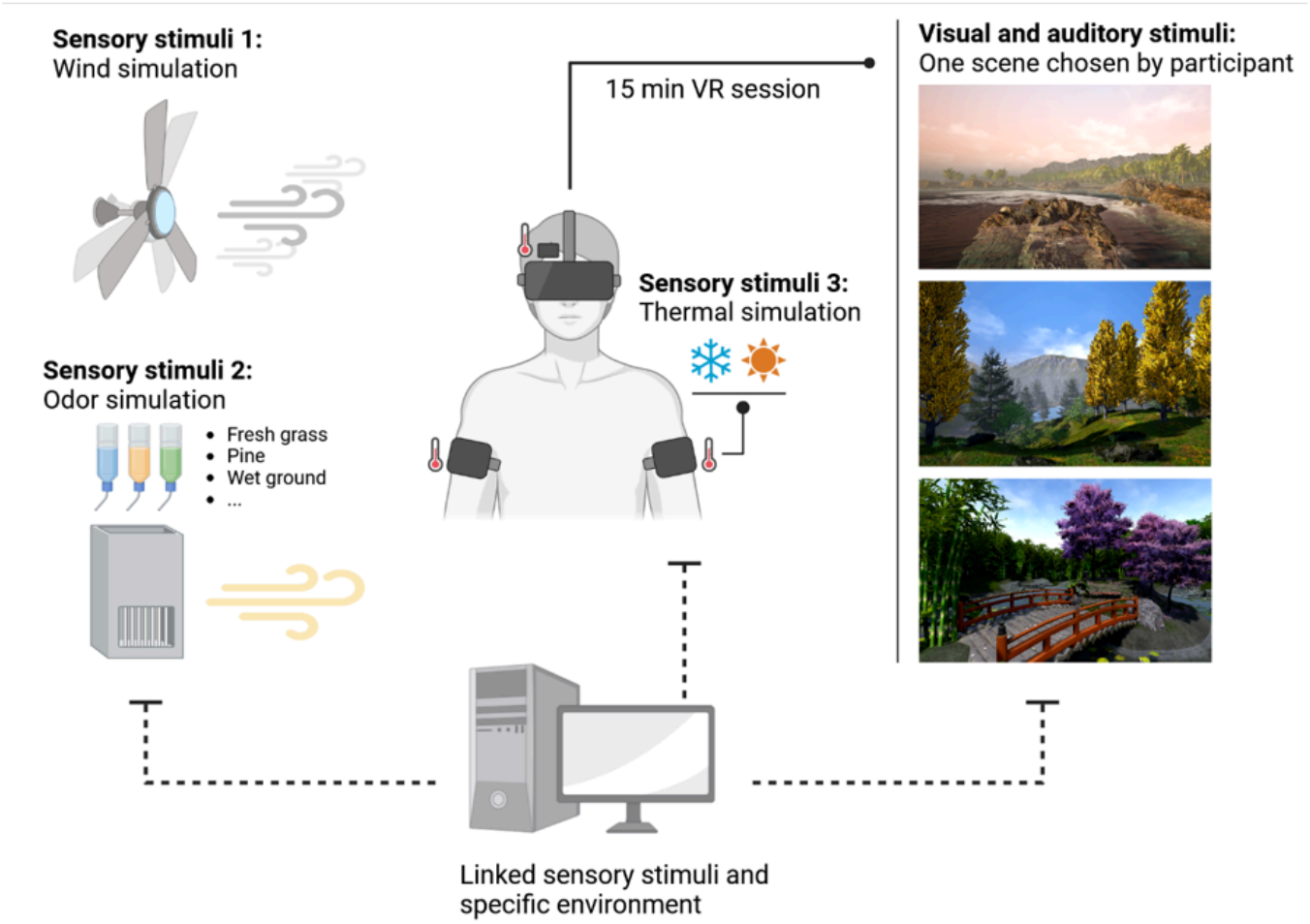


Figure 8

Illustration of the multisensory VR scenarios incorporating wind, olfactory, and thermal stimuli. Wind was delivered using three external fans, scents were provided through a digital scent generator, and thermal stimuli (hot and cold) were delivered via wearable thermoelectric devices placed on the arms and head.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SciRepMultisensoryVRSupplementaryInfo.docx